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The Editor welcomes writers interested in air pollution problems and encourages them to use the pages of this journal for the expression of their opinions. But neither he nor the Association assumes responsibility for the validity of the opinions expressed herein.

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Sampling For Airborne Radioactivity*

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May 1955 - Feb. 1958
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As the nation's industrial complex grows, one of its attendant evils—environmental pollution—grows apace. Perhaps no segment of this complex grows more rapidly at present than the atomic energy industry. Responsible officials are gradually becoming aware of the potential for pollution of this new giant. The problem is complicated by security requirements and by virtue of the inability to sense the presence of radioactive contaminants. The present contribution considers some of the general aspects of one segment of this relatively new problem—airborne radioactive contamination.

Nature of Radioactivity

Atoms which are unstable as a result of the relative numbers or configurations of the constituents of their nuclei are said to be radioactive. In the process of achieving greater stability, these nuclei undergo a process of disintegration, one of the results of which is the emission of energy in the form of radiation. Based on its origin, this is termed nuclear radiation, to distinguish from other types of radiations which result from extra-nuclear phenomena. It is important to distinguish between the source of the nuclear radiation (the radioactive material) and the radiation emitted therefrom.

Most chemical elements have several forms, differing in the mass of the atomic nuclei, but not in chemical properties. These different forms of the same element are called isotopes. There are over 300 naturally occurring isotopes of some 90 chemical elements. Of these, about 16% are radioactive, the remainder stable. In addition, there is a growing list of over 600 different radioactive isotopes which have been produced artificially—all in the last 15 years.

Each radioactive isotope has distinctive properties in the way of type and energy of radiation emitted, and rate of decay. The latter property is commonly characterized in terms of half-life—the time required for one half of a given number of atoms to undergo disintegration. Half-lives of the various isotopes vary from fractions of a second to billions of years.

There are several types of nuclear radiations. We need consider three types—alpha, beta, and gamma. Alpha and beta radiations are composed of fast-moving, discrete particles—helium nuclei and electrons, respectively. Gamma radiation is nonparticulate, being electromagnetic in character, and differing from visible light only in wave length, and therefore energy.

The primary effect of the various types of radiation is the same—the transfer of energy to the medium traversed, usually resulting in ionization, or excitation. For this reason, nuclear radiations are often referred to also as ionizing radiations. Nuclear radiations are not detectable by any of the human senses. Detection and measurement are made possible by use of instruments which measure some effect of the radiation—commonly, ionization. Ionization is also the principle basis for damage to biological systems by nuclear radiations.

Due to differences in range of travel and specific ionization, the various types of radiation vary in their biological effectiveness. Alpha particles are relatively heavy and highly charged. Thus, their penetration is very low, but their specific ionization (ionization produced per unit path length) is very high. Beta particles are much lighter and lesser charged. Their penetration is moderate. Gamma rays are weightless, chargeless, and highly penetrating. The amount of energy associated with emitted radiation varies between isotopes. Obviously, the greater the energy of the radiation of a given type, the greater its biological effectiveness. These properties have an important bearing on both detection and biological effectiveness.

Biological Effectiveness of Nuclear Radiations

This is not the place to consider basic mechanisms of radiation damage to biological systems. It can be generalized that the biological effect is directly proportional to the radiation dose per unit volume and to the radiosensitivity of the body organ irradiated.

There exist 2 rather different categories of hazard. The first of these, which we shall only mention, occurs when the source of radiation remains outside the body. This is referred to as the external radiation hazard. Gamma radiation is the most important type here, due to its high penetrability. Beta radiation affects the surface layers of the body (skin) only, although this can be serious. Alpha radiation is generally considered to afford no external hazard. The distinctive feature is the ability to eliminate the external hazard by removing the source of radiation from the proximity of the person, or vice versa.

The other category of hazard is internal—i.e., when the source of radiation is taken into the body. In this case it is more difficult to separate source and object. Individual radioactive isotopes vary in their degree of internal

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hazard, depending on: (1) type of radiation emitted, (2) energy of the radiation, (3) rate of decay of the material, (4) distribution of the material in the body, and (5) the rate and completeness of excretion of material from the body. The latter two factors are functions of the chemical nature and the physical state of the contaminating material.

The relative internal hazard of the 3 types of radiation is just the reverse of the external case. Intense damage is effected in a small volume around sources of alpha radiation. Where these sources reside in critical body organs, an extreme hazard may result. Beta radiations are again intermediate, but of generally greater concern than from external sources. Gamma radiation is of lesser significance, except for the difficulty of removing the source.

It is perhaps worthwhile to interject at this point the fact that the body is continuously being subjected to nuclear radiations from cosmic rays and naturally occurring radioactive materials. Radiation exposure is nothing new. The rapid growth of the atomic energy industry, however, adds greatly to the potential for exposure.

The 2 principle routes of radioactive materials into the body are, of course, ingestion and inhalation. There is reason to believe that, except under most unusual conditions, inhalation offers the more significant potential.[1] The remaining discussion will be devoted to the significance of radioactive materials as air pollutants, and specifically as this relates to an inhalation hazard.

The distinguishing characteristic of a radioactive aerosol is its extreme toxicity. Maximum permissible concentrations represent fantastically small amounts of matter, being of the order of μ-μg/m.^{3} for some isotopes. This compares with measurement of many chemo-toxic materials in mg./m.^{3} Of course, radioactive particulates are mixed environmentally with much larger amounts of non-active materials.

Aside from the nature of the particular radioisotope which is inhaled, the size and solubility of the particles of which it is a part are important. Radioactive particles behave in the same way as other particles in being deposited in the respiratory system. In the nasal system, all particles larger than about 5 μ diameter are filtered out. The efficiency of nasal retention decreases with particle size, reaching essentially zero for 1 μ particles and smaller. Over-all respiratory retention is virtually complete for about 5 μ particles, and decreases to a minimum of some 25% for 0.25 μ particles. The lower retention of fine particles is attributed at least partially to the fact that they may be inhaled, then exhaled again without ever impinging on any surface.[2] Currently accepted standards for maximum permissible concentrations of airborne radioactivity[3] are based on the following assumptions regarding retention of inhaled particulates: (1) In the case of soluble compounds, 25% is retained in the lower respiratory tract. From this point it goes to the blood stream, its fate within the body then depending on the chemical nature of the material. Further, another 50% is held in the upper respiratory tract and subsequently swallowed. (2) In the case of insoluble compounds, it is assumed that 12% is retained in the lower respiratory tract. The rest is exhaled or swallowed.

In performing necessary computations, one must make assumptions, and the ones made are probably as good as any for general use. There is evidence, however, that particle size has a marked effect on body retention. One study[4], for example, indicates that retention of insoluble particles may vary from 1.2 to 38%, depending on the particle size distribution.

Further evidence of the importance of the particle size factor is shown by the following statement[5]: "A maximum permissible air concentration for mixed fission products following a nuclear detonation has been established by the U. S. AEC upon the recommendation of an advisory panel of experts. This concentration is 100 micromicrocuries/m.^{3} of air, averaged over a 24-hr. period. Since particles between ½ and 5 μ are most likely to be retained in the lung, the maximum permissible concentration is 1 micromicrocurie/m.^{3} of air if the radioactivity is associated with particles less than 5 μ in diameter."

Once inside the body, the site of deposition of the radioactive material assumes some importance. Frequently, these materials tend to concentrate in certain specific organs of the body. For that reason, calculations of resulting exposure are made on the basis of the body organ receiving the greatest radiation dose, the so-called "critical organ." For inhaled insoluble particulates, the lung itself is the critical organ. For soluble material, the chemical nature determines the critical organ. The most striking single example is concentration of iodine in the thyroid. As an aside, it might be pointed out that widespread use is made of this phenomenon in medical diagnosis, therapy and research.

Exposure to Airborne Radioactive Materials

We might now examine the potential sources of airborne radioactive particulates, and indicate who might be exposed to them. Radioactive aerosols are produced in the atomic energy industry: (1) as dusts in the cooling air from some nuclear reactors; (2) as mists and fumes arising during the separation of plutonium from fission products; (3) as dusts from the mining, transport-

(1) Eisenbud, M., Blatz, H., and Barry, E. V., "How Important Is Surface Contamination," *Nucleonics, 12,* No. 8, 12-15 (1954).

(2) Morgan, G. W., and Buchanan, C. R., "Air Contamination and Respiratory Protection in Radioisotope Work," *AECU Report 2821* (1953).

(3) "Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water," National Bureau of Standards Handbook No. 52 (1953).

(4) Burnett, T. J., "Sampling Methods and Requirements for Estimating Airborne Radioparticulate Hazards," *ORNL Report CF-52-11-1* (1952).

(5) "Assuring Public Safety in Continental Weapons Tests," *Thirteenth Semi-Annual Report of the U.S. Atomic Energy Commission* (1953).

ing, and storing of uranium ore; (4) as dusts and mists in manipulating and processing radioactive ores; (5) during incineration of radioactive wastes and by-products; (6) during laboratory and plant operations in various phases of atomic energy work; and (7) during detonation of atomic weapons.

Potential exposure from these sources may be considered in 3 categories. First, there are those persons working in mines, plants, or laboratories where radioactive aerosols are produced. In the second category are the areas immediately adjacent to such installations, for distances up to several miles. Lastly, we might consider areas extending over hundreds or thousands of square miles.

We may state categorically that the Atomic Energy Commission and its contractors have done an outstanding job in protecting the people who work in their installations and those who live nearby. The safety record has been little short of phenomenal in view of what might have happened.

Widespread environmental contamination is a more complex problem. Insofar as we have knowledge, the only appreciable source of widespread contamination is atomic weapons testing. We do not, as yet, know with certainty what additional problems of this type will confront us with the vast expansion of the atomic energy industry which will undoubtedly occur in the foreseeable future. We certainly do not know all of the things that will happen in the event that atomic weapons are used in war on our country. There is a strong suspicion that inhalation and ingestion of radioactive materials may represent a serious, long-range problem.

Sampling and Measurement of Airborne Radio-particulates

To this point, there has been an attempt to point out some of the reasons why airborne radioactivity is of concern. It is obvious that if hazards from this source are to be recognized and controlled, there must be some mechanism for collection of adequate samples and for making appropriate determinations of the content thereof.

Sampling is a problem, the difficultness of which is shared by all phases of scientific endeavor. The universal, and never quite attainable, goal is that phantom — the "representative sample." Even the term is difficult of definition. In its simplest sense, it means to obtain an aliquot which is identical, in all of its important (for the purpose at hand) aspects, with the population which is of interest to the sampler. Every sample is representative of something. The essential question is—how far into the medium as a whole is it safe to extrapolate results obtained on a given sample of the medium? Statistics is a useful tool as an assistant; still, much is left to be desired.

Sampling of the air for particulate contamination represents one of the more difficult of sampling problems. Efficient samplers have been developed, but the problem of extrapolation is often acute. For example, in a laboratory or plant there frequently exist vast differences in concentrations of pollutants over limited distances. Environmental sampling is made complex because of the vagaries of micro-meteorology. In spite of this, much useful information is obtainable. Inherent limitations, however, must never be overlooked.

The simplest and most widely used type of sampler for airborne particulates is one based on concentration of the sample by filtering. Any device which can be used to pull air through an appropriate filtering material is satisfactory. In the authors' laboratory, relatively inexpensive commercial vacuum cleaners and Hollingsworth and Vose H-70 filter paper are used, with rather good results.

The critical features of this type of sampler are: (1) the efficiency of the filtering material, (2) particle size of contaminants, and (3) the atmospheric concentration of contaminants. It is quite common to obtain sampling efficiencies of 95 to 99% with filter paper samplers. Use of the so-called molecular, or membrane, filters now available should increase this efficiency, although not representing the perfect solution.

Other types of samplers in common use are electrostatic precipitators, impingers, and cyclone separators. Each has its advantages for specific problems, and disadvantages for universal use.

All of the samplers so far mentioned are more or less useful in determining gross concentrations of contaminants over a fairly wide range of particle size. The importance of the particle size factor has been pointed out. It is, thus, frequently desirable to ascertain the particle size distribution of airborne contaminants. Again, no single method or technique can provide adequate information of this type in all circumstances.

Optical and electron miscroscopes are used, but procedures are relatively tedious, and techniques not easily adapted for routine work. The thermal precipitator is quite useful under certain conditions in determination of very small particles.

Perhaps the most widely useful sampler for particle size determinations is the cascade impactor. This instrument can be considered as a sort of multiple jet sampler. It employs a series of jets of decreasing areas and collecting slides arranged in tandem. The first stage removes the largest particles, and each succeeding stage progressively removes a segment of the upper size range of the remaining distribution. The usual model has 5 stages, the final one of which is a filter paper. Good results are obtained in the range between 0.2 and 50 μ diameter. Below 0.3 to 0.6 μ sampling is efficient but there is not good characterization of particle size.[6] There are difficulties of calibration and so on, but by and large this is a good instrument for the purpose.

Once a sample has been obtained, the problem becomes one of analysis for radioactive content and of evaluation

(6) Stokinger, H. E., and Laskin, S., "Air Pollution and the Particle Size Toxicity Problem," *Nucleonics, 6,* No. 3, 15-31 (1950)

of possible hazards. In addition to such parameters as volume sampled, representativeness of sample, and particle size distribution, a determination of the isotopic species present must be made. It is also desirable to determine the physical and chemical nature of the particulate material, but only when the exact source of the pollutant is known can this be evaluated without elaborate analyses.

If the collected sample is sufficiently active (in radioactive content) and provided a complex mixture of isotopes is not present, identification of specific contaminants is usually possible. This is done by measurement of type and energy of radiation emitted and of the rate of decay (half-life). One must then equate the results with accepted values for maximum permissible concentrations of each isotope present.

One additional complication is the presence in the atmosphere of naturally occurring radioactive materials. These are principally the radioactive gases (radon and thoron) and their decay products. They become adsorbed on dust particles and are collected by the air sampler. The activity from this source can cause considerable complication in interpretation of data on the content of artificial contaminants if the determinations are made soon after sample collection. By allowing the sample to stand for about 24 hr. between collection and measurement, however, this complication is effectively eliminated. Most artificial contaminants of interest have half-lives of sufficient length to allow this procedure to be followed.

If the atmospheric concentration of these natural contaminants were relatively constant, appropriate corrections could be made for them. Such is not the case; and the fact that their concentration varies between rather wide limits is of considerable interest in certain meteorological investigations.

Some airborne radioactivity samplers are in use in which the detection and measurement equipment is made an integral part of the apparatus. Filter paper is inserted in a roll. Air is drawn through a segment of the paper. After a given interval of time, the paper is automatically caused to move, so that the exposed segment is placed near an appropriate detecting element, and a new segment of paper is exposed. A recording mechanism may be attached to the detector, making an automatic, continuously operating assembly.

Still another technique involves passing air directly into a measuring chamber, without concentration.

Constructive Use of Radioactive Aerosols

Aside from an interest in the possible hazards of airborne radioactivity, a potential exists for making constructive use of the phenomena involved, particularly in meteorological research. It is feasible to "tag" air currents with radioactive aerosols, and to study the subsequent behavior of these currents by tracking the radioactivity. This should be possible with amounts of material well below hazardous concentrations. Meteorological information could be obtained with this technique that could probably be gotten in no other way. Some caution is indicated, however, primarily because any additional sources of environmental radioactive contamination must be carefully scrutinized, and a balance struck between advantages and disadvantages.

Some of the possibilities are indicated by work of the authors' laboratory. These indications are on a very gross basis, as no control could be exercised over the important factors involved.

During the last 3 atomic weapons testing programs in Nevada, we have operated a statewide air-sampling program. From 10 to 20 rather widely scattered sampling stations have been used. After the announcement of each test shot, a prediction was made of the general path that the radioactive residue should follow. Predictions were based on meteorological data available from regular U. S. Weather Bureau sources. Observations from the air samplers were then compared with the meteorological predictions. There have been handicaps in that we could sample only in California, and prevailing winds are such that most of the material goes to the east and northeast, away from California.

Nevertheless, some interesting results were obtained. Of 25 test shots of which there is definite knowledge, radioactive material from about 16 was detected at 1 or more of our sampling stations. The amount and distribution of material has been highly variable. A qualitative correlation was made between prediction and observation for each test. The correlation was classified as good to excellent in 18 cases and as fair to poor in 7. In general, as may be expected, predictions were reasonably accurate when wind velocities were moderate to high, and when winds at all elevations were from the same general direction. In other cases, results differed appreciably from predictions. There were exceptions, however, to both examples.

Conclusions

The rapid growth of the atomic energy industry adds another dimension to the field of environmental pollution, but there is, at present, no evidence to indicate cause for acute widespread concern over the problem. It is not too early, however, to develop plans to cope with an acute situation, should it arise. As a minimum, widespread periodic sampling for airborne radioactivity is indicated.

As the base of the atomic energy industry broadens, and as operating costs become more of a factor, constant vigilance must be maintained to assure that the same high safety standards now prevalent are maintained.

Nuclear energy offers much that can serve to better man's lot. However, it is incumbent upon responsible officials and agencies to insure that the populace is protected from associated hazards, interfering as little as possible with development of beneficial aspects.

Controlling Atmospheric Contaminants in the Smelting and Refining of Copper-Base Alloys*

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That the production of brass and bronze ingot is important to the national economy is indicated by the fact that each year more than 600,000,000 lb. of copper-base alloys are produced in the United States. Virtually all such manufacture is done by secondary smelters. This paper concerns itself with the examination of equipment at a modern secondary smelter and a discussion of function and operation from the viewpoint of the control of atmospheric contaminants.

The most recently constructed division of H. Kramer and Company is that which is now operating in El Segundo, California, the plant resulting from experience gained after decades of production by the parent firm and its Ajax Division. Before construction of this plant, information and data regarding the proposed installation were submitted to the Los Angeles County Air Pollution Control District with applications for authority to construct the various production and control units. A series of conferences between company representatives and smog-control engineers followed, which resulted in the approval of modified plans by the Air Pollution Control District. The refining and alloying equipment which was authorized for construction included three 100,000 lb. capacity reverberatory furnaces, two 6,000-lb.-capacity rotary furnaces and two 750-lb.-capacity tilting crucible furnaces. The pre-processing equipment† consisted of a 12,000 lb./hr.-54-in. cupola and a 6,000-lb./hr. radiator sweat furnace. With the exception of the tilting furnaces, all of the production and pre-processing units are served by dust-collection equipment described later in this paper.

The selection of the refining and alloying equipment was based upon the fluctuations and variations in industrial quantity demand for the numerous alloys produced in secondary smelters. The size of the cupola was determined by the quantity of slag generated during normal operations and by the estimated amount of normally procurable low grade residues. The radiator sweat-furnace design was developed at the Chicago plant and duplicated for use in the Los Angeles plant.

†Pre-processing equipment may be defined as equipment which is used in the processing of scrap, slag and other low grade materials, prior to their being introduced into the refining or alloying processes.

*Presented at the First Semi-Annual Technical Conference of the Air Pollution Control Association at Los Angeles, California, November 4-6, 1954.

Refining and Alloying Equipment

Tilting Crucible Furnaces

Each tilting crucible furnace is a refractory-lined steel shell containing a silicon carbide or clay crucible in which the metal is melted. The melt is achieved by dual 3-in. Fisher gas burners in each furnace. The necessary combustion air is supplied to both units by a single 600-cfm. capacity blower at 20 oz. pressure. The furnaces can also be fired with oil, in which case the Fisher burners are replaced by Hauck oil burners. The same combustion blower is used in either case.

The furnace is manually charged and is used solely for alloying. Various metallic and nonmetallic fluxes are used. The fluxes may be oxidizing, reducing, or inert, depending upon the type of metals to be melted and the conditions desired. The total time for a single heat does not exceed 2 hr. Of this time, less than 30 min. is allotted to charging. The pouring consumes only 10 min. The remainder of the time is used for melting, control analysis, and adjustment to prescribed specifications. Fumes evolved during the operation are caused by the volatilization of zinc from the alloy. This loss is minimized by the proper use of fluxing agents.

The plans called for enclosing the entire unit in a steel hood with a sliding door on the charging end. After production was started on the reverberatory and rotary furnaces, however, it was found that the only use for

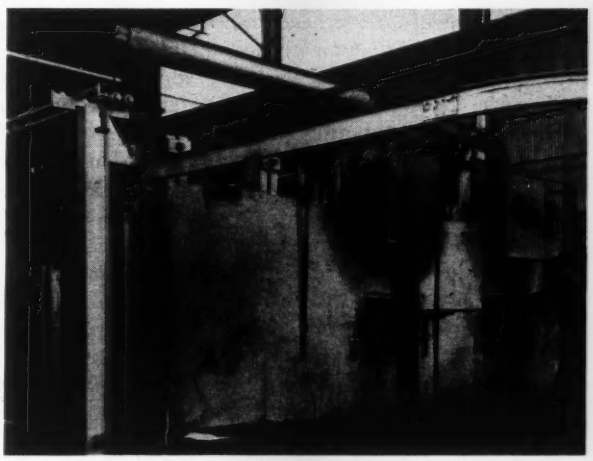

Fig. 1. 50-Ton Reverberatory Brass Refining Furnace.

Fig. 2. Pouring Reverberatory Furnace with Controls off.

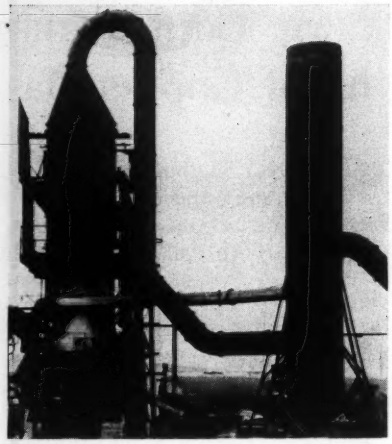

Fig. 5. 54-Inch Cupola. ➡

Fig. 3. Pouring Reverberatory Furnace with Controls on.

the crucible furnace would be for copper-base alloys containing no zinc or a maximum of 5% zinc. Therefore, it was decided not to hood these furnaces but to operate under limiting conditions with the approval of the local authorities. This was done, and the Los Angeles County Air Pollution Control District inspected and approved the operation subject to the 5%-zinc-content limitations and the use of suitable fluxes.

The use of these furnaces is limited to producing alloys which are ordered in such small quantities as to make it uneconomical to use a larger furnace and stock a larger quantity. They are also used for various types of special alloys and for test heats and research problems where it is necessary to duplicate the conditions that the finished product will be subjected to in the casting foundry.

50-Ton Reverberatory Brass-Refining Furnaces

The reverberatory furnaces are supplied with two 5 in. No. 50 Maxon "sticktight" flame-retention-nozzle gas burners (Fig. 1). Combustion air is provided by a multistage centrifugal blower having a capacity of 1150 cfm. at 28 oz. pressure. The furnaces are equipped with oil "stand-by," using a preheated No. 5 industrial oil.

These furnaces are charged through a top charging door by means of an overhead crane. The motion of the door is controlled by an air cylinder. The material normally charged is composed of various grades of scrap brass and bronze. During the charging cycle all of the furnace openings except the burner ports are completely closed and luted with a clay compound to prevent inspiration of air at any point other than the burner ports and the charging door.

During the refining process, a 1¼ in. diameter steel pipe delivering 160 cfm. of air is inserted below the surface of the molten metal. This operation volatilizes and oxidizes up to 750 lb./hr. of zinc in the metal bath. This "blowing" procedure may vary in duration from 10 min. to several hr. in any 24-hour period. While this refining process is under way, all doors and openings with the exception of the burner ports are closed.

The pouring operation for the furnace is carried out by piercing the refractory breast with a steel bar (Fig. 2 and 3). Metal flows from this opening into a tilting ladle by gravity. The pneumatically activated tilting motion of the ladle causes the metal to flow into ingot molds. Hoods are provided at both the side slagging doors and the pouring spout.

The reverberatory furnace is the key production unit in a secondary smelter. Its function is to produce in quantity brass and bronze ingot. For all its versatility as a production unit, it is, nevertheless, the greatest potential dust and fume violator. Therefore, the reverberatory units are the prime consideration in the determination of the size of the control unit required. It is a matter of record that, before the era of scientific dust and fume control, the discharge from a 100,000-lb. reverberatory brass furnace was 3,000 - 4,000 lb./day; more than 1,000,000 lb./yr. were emitted into the atmosphere. Such voluminous discharge, if not controlled, could easily coat a plant and the surrounding community with a white layer of zinc oxide.

6,000-Lb. Rotary Furnaces

The rotary furnaces (Fig. 4) are primarily smelting and

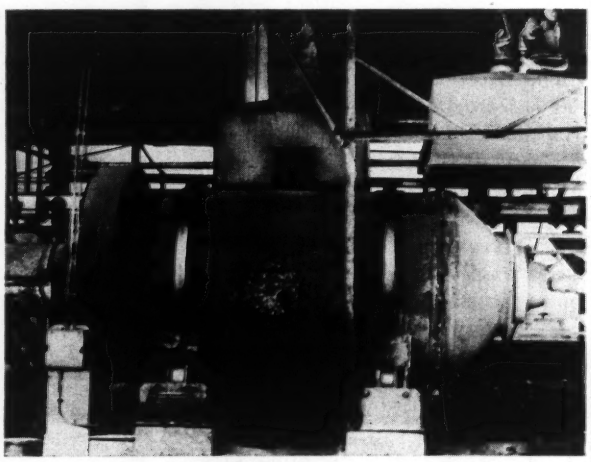

Fig. 4. 3-Ton Rotary Furnace.

melting furnaces and, under normal conditions, no air refining is performed. Each unit is heated by means of a single 4-in.-Hauck No. 584 burner. The combustion air for both furnaces is supplied by a single blower having a capacity of 640 cfm. at 24 oz. pressure. "Stand-by" oil is provided for use when local gas is unavailable.

Materials of known analysis are manually charged into the furnace. Since the burner door must be swung out of position during the charging, no firing can take place during that period. After the charging is completed, the door is swung back into position, and the furnace is fired until the molten state has been attained. No firing takes place during the slagging operation. Hoods have been installed over the charging door and pouring spout.

The fluxing includes the addition of such components as sodium carbonate, silica, calcium carbonate, and other metallic oxides. The exhaust from the furnace is drawn through a brick-lined 11-in-I.D. horizontal duct surrounded by a water jacket.

Each furnace operates on an 8-hr. cycle, pouring twice during that period, and processes an average of 1500 lb./hr. In an 8-hr. cycle, the slagging time is about ½ hr., and the charging time is about 1 hr. The copper content of the resultant product may vary from 58 to 93% while the zinc composition may vary from 0 to 40%.

Pouring is effected by piercing the refractory breast on the side of the furnace and rotating the unit so that it empties by gravity. The metal stream is directed into a preheated ladle which is tilted by an air-operated device. The ladle empties into ingot molds.

The function of the rotary furnace is to produce medium quantities of stock specification ingot. Another important use is to produce alloys which are difficult to control chemically in large quantities. This is especially true of aluminum bronze and certain of the manganese-bronze alloys. The low impurity allowance of these copper-base alloys is one of the most important limiting factors in producing an ingot which can meet prescribed physical properties. It is, therefore, impractical to produce these alloys in a reverberatory furnace which has been previously used for smelting an alloy containing elements having a deleterious effect on aluminum and manganese bronze.

Pre-Processing Equipment

54-Inch Cupola

The cupola is used for the reduction of copper-base alloys, slags, and residues (Fig. 5). It is 54 in. in diameter at the tuyere line. The practice is to maintain a cold top in the cupola in order to hold down the amount of fly ash and dust. For the same purpose, the cupola is operated under a slight back pressure.

The cupola consumes approximately 2,000 lb./hr. of foundry coke. It has ten 3-in. tuyeres equidistantly spaced around the furnace, through which is delivered 4,000 cfm. of air at 20 oz. pressure. Temperature at the tuyeres is approximately 2300° F.; gas temperature at the top of the water jacket before it enters the hood is approximately 600° F.

Precalculated charges of slags, residues, coke, and fluxes are dumped into the charging hood by specially designed buckets which are carried by an overhead crane. 12,000 lb./hr. of copper slags and residues can be processed. In addition to the coke-and-metal-bearing slags and skimmings, appropriate amounts of chemical fluxes and reducing agents are used for the purpose of separating the metal from the gangue, and also to properly balance the slag produced so that it will be fluid and free from metal droplets.

The slag produced during the reducing operation is eliminated through a slag spout, and analyzed at regular intervals during each 24-hr. period. The results of the slag analysis are a direct indication of the efficiency of the blast operation. The total copper, tin, and lead should be less than 2%. Slags containing higher percentages of these elements can be rerun in the cupola.

The product of the cupola, commonly called "black copper," is an alloy of copper, tin, lead, zinc, and nickel, with a relatively high percentage of undesirable iron and sulfur. The metal is analyzed and subsequently recharged into the reverberatory furnaces where it is refined and adjusted to a specification ingot.

A cupola is a necessity in a modern secondary smelter because it provides a means of converting a plant's own slags into usable material, the economy of which (as against shipping and selling the slag) is obvious. It is also a means of salvaging the metallic content of skimmings, slags, and drosses which are produced in the casting foundries. The cupola salvages not only copper, but also recovers tin and lead without any appreciable loss.

Radiator Sweat Furnace

The radiator sweat furnace is used for the separation of scrap automobile radiators into their component parts (Fig. 6). Auto and truck radiators are normally composed of top and bottom brass tanks fabricated from a 70% copper, 30% zinc alloy. The radiator fins are usually pure copper, while connections are made of steel, brass, or bronze. All of these parts are held together by a solder.

The radiators are charged into the furnace and shaken vigorously as they move on an inclined plane through the heating area. The temperature of the furnace chamber is thermostatically controlled. At the proper temperature the solder melts and flows into a trough which, in turn, directs the flow into iron molds. Since copper, brass, and iron are not affected by the low temperatures used, they pass through the heating chamber without melting and are cooled in a water pit.

Emission products from such substances as antifreeze, soldering salts and water are exhausted into the dust-collection system. Other possible products are the result of various combustible hose connections, etc.

The gases and mists from this operation contain no

Fig. 9. Duct Work and Settling Chamber Ahead of Dust Collector.

Fig. 6. Radiator Sweat Furnace.

Fig. 7. Collection System for Radiator Sweat Furnace.

zinc or zinc oxide, and the emissions, if they were collected, would have no commercial value. In addition to the undesirability of collecting a worthless product, there is the danger of contaminating the products caught in the baghouse designed to serve the other production and pre-processing equipment.

Therefore, it was necessary to install a separate collection system for the radiator sweat furnace (Fig. 7). Because of the small quantity and the nature of the emissions, a wet collector was selected in which the discharge is scrubbed by a slightly alkaline water solution. The emissions from the sweater are exhausted to the collector by means of a 15 hp. fan having a capacity of 6000 cfm. at a static pressure of 8½-in.-w.g. The wet-type collector consists of a vertical cylindrical tower containing 3 shelves of impingement stages and an entrainment separator above all. The collector tower is flat on top but has a conical bottom. Air-containing emissions from the sweater enter the collector through a tangentially directed 17-in.-diameter duct placed just above the cone. The tangentially introduced air is made to follow a spiral path as it is drawn upward through each impingement plate.

Much of the suspended solids is thrown out of the air stream by means of the cone-shaped bottom serving as a wet cyclone. The mists and gases, or remaining solids, are subjected to the turbulent scrubbing action of the alkaline water solution which is introduced at a point above the center of the top impingement plate. The scrubbing agent flows counter-currently downward, cascading from plate to plate as the dirty air stream spirals upward. The entrainment separator acts to coalesce the fine droplets so that they do not pass out through the clean air outlet atop the collector.

A 30-gal. settling and dewatering tank is used for continuously settling solids and separating liquid sludge.

The sweat furnace is of importance as a pre-processing unit because, as a result of this operation, the chemical content of the recovered products becomes known. This is an asset in formulating "charges" for the reverberatory furnace. Also, the separation of the more valuable "white" metal from the "red" metal is achieved. The recovered solder can be sold or used (for tin and lead) in the secondary smelter.

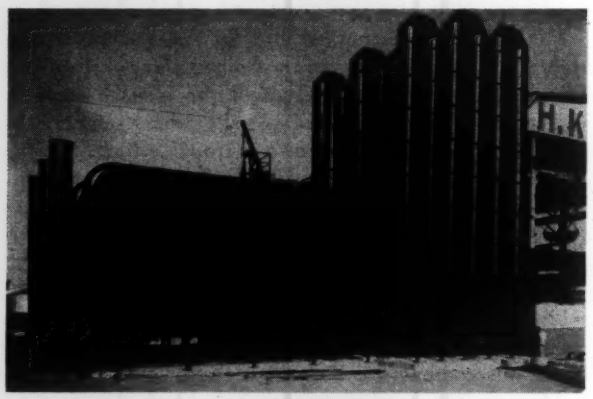

Fig. 8. Dust-Collection System.

Dust-Collection System

Each of the 3 baghouses in use in the Kramer California Division is an automatic bag-type dust arrester (Fig. 8). The baghouses are connected in parallel and each has a net filter-cloth area of 9,072 ft.² and a 50 hp. exhauster handling 18,144 cfm. With all 3 units in simultaneous operation, a total of 54,432 cfm. is available, which is more than adequate to handle the basic equipment at a filter ratio of 2.45 to 1. The dust-laden gases enter a settling chamber to permit the separation of the heavier particles and then pass through radiant cooling towers before they reach the baghouse (Fig. 9).

Each baghouse has 7 sections with 108 bags/section. Shaking is automatically performed on a time cycle, with the section shaken being shut off. A temperature alarm, visible and audible, has been provided as a warning should baghouse temperature exceed 250° F.

The material collected in the baghouse is what the smelting industry refers to as "flue dust." At this plant,

the dust has been found to have an average analysis of 87% zinc oxide. The balance is composed of other metal oxides, sulfates, and oxychlorides. The zinc oxide is the result of volatilization and subsequent condensation of vaporized zinc. Zinc oxide fume under the microscope has a spiney appearance, which explains its tendency to agglomerate into larger particles and permits easier filtration. It has been shown that before agglomeration, zinc oxide fume is approximately 0.05 μ in size (⅛ the particle size of tobacco smoke).

There are today many synthetic and natural fibers which are available for air-stream filtration. None is universally applicable, each having its field of application and its weaknesses. In the final analysis, each firm must evaluate the many variables in the filtration problem and arrive at an acceptable compromise. In addition to the particle size, shape, and velocity, such factors as cloth porosity, weight and weave, nap, resistance to chemicals, method of shaking, and temperatures involved must also be considered. After tests with many fabrics, we decided to use orlon because of its chemical and thermal resistance and its general physical stability. With small holes and tears being repaired, the average bag life has been 2 years.

The control equipment is so designed that very little direct labor is involved. One man on each shift is responsible for the maintenance and control of the baghouse. He is charged with the lubrication of all moving parts and his duties also include the routine inspection of the baghouse cells and the changing and repair of bags, when necessary. Temperature-control charts on a 24-hr. automatic recording device are daily checked by the plant superintendent. These readings enable him to review the charging practices of the previous day.

The dust-and fume-control system using orlon bags was designed and installed to serve 2 of the 3 reverberatory furnaces, 2 rotary furnaces, 2 crucible furnaces, and the cupola in simultaneous operation. The most vital factors in the calculation and design of the size of the collector were the rate of fuel consumption and the volumes of air to be removed from the vicinity of the charging doors, pouring spouts and other open sources of emission. The temperature of the effluent gases from the furnaces is in the maximum range of 2300° to 2500° F.

Even after dilution of these hot gases with relatively cool air drawn in through the various hoods serving each furnace, it was apparent that the resultant temperature of the gas mixture would be in excess of that which could be safely handled by any known air-filtering medium. Calculations revealed that the temperature of the gases would be in the range where radiant cooling could be effectively utilized. Since it had been decided previously that orlon was to be used as the filtering medium, the temperature of the gases entering the baghouse was limited to a maximum of 250° F. Adequate radiant cooling was provided to assure that this temperature would not be exceeded.

Calculation

Example for calculating the volume of gases from each reverberatory furnace to be handled by the exhaust system and baghouse:

Products of combustion for natural gas with a heating value of 1100 Btu/ft.^{3} at 20% excess air = 13.86 cfm./cfm. of gas at 60° F.

(110 cfm. natural gas) (13.86 cfm./cfm.) = 1520 cfm. of products of combustion at 60° F.

Volume of gas from the air blowing operation is 160 cfm. at 15 psig.

Volume at standard pressure is

$$(160 \text{ cfm.}) \left(\frac{29.7 \text{ psi.}}{14.7 \text{ psi.}}\right) = 323 \text{ cfm. at } 60° \text{ F.}$$

Volume of air drawn into the system through the hoods serving the furnace was determined by the location and shape of the hoods. It was determined that 100 fpm. was an adequate indraft velocity for these hoods. There are 3 hoods/furnace with a total face area of 19.58 ft.^{2}

Volume = (100 ft./min.) (19.58 ft.^{2}) = 1958 cfm. at 60° F.

The total volume of gases to be handled from this furnace is

$1520 + 323 + 1958 = 3801$ cfm. at 60° F.

Correcting this volume to baghouse conditions, using a temperature of 270° F., the volume will be

$$(3801) \left(\frac{460 + 270}{460 + 60}\right) = 5340 \text{ cfm. at } 270° \text{ F.}$$

This method was employed to calculate the volume of gases to be expected from each of the furnaces used in this plant.

Conclusion

This paper has discussed the production equipment used in a secondary smelter, the basis for selection of suitable controls, and operational and economic considerations.

The construction of the correct production and control units is only the beginning. The effectiveness of the equipment is directly proportional to the ability of the production staff. Collecting the dust and fumes is of paramount importance from an economic standpoint. However, the value of the captured emission product is only a fraction of its worth were it retained in the furnace. The goal of the operation is, therefore, to minimize emissions.

Correct procedures to charge, flux and melt scrap copper and copper-base-alloy materials are not described in the literature. The 2 sources of knowledge are research and experience. The dual aim of all operational research is to minimize the loss from the items charged and simultaneously collect the maximum amount of all volatilized emissions.

In the hands of the production staff lies the answer to economic survival. Equipped with adequate produc-

(Concluded on page 26)

Engineering Waste Disposal To Prevent Air Pollution*

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Los Angeles County Sanitation Districts

Disposing of waste materials so as to prevent air pollution is a recent requirement in the history of waste disposal. The elimination of nuisance and the protection of public health have in the past dictated what practices are acceptable and which must be rejected. Lately there has developed the additional necessity that waste disposal be accomplished without pollution of the atmosphere, a problem concomitant with highly centralized urban development. Sanitary engineers have conducted research on the disposal of liquid wastes (sewage) for almost a century, but similar study on the disposal of solid or semi-solid wastes (refuse) is an innovation of the past few years and much work remains to be done.

Collecting and Disposing of Sewage

The elimination of air pollution resulting from sewage commenced with the advent of sanitary sewers for the collection of such waste just about 100 yrs. ago. That this caused considerable concern and alarm among engineers fearful of health hazards and air pollution is documented by writers of that period who envisioned the permeation of "sewer gas" into the soil and ultimately into the homes and atmospheres of the cities, creating intolerable odor conditions and spreading diseases. It is indeed fortunate that this concept has proved invalid, as demonstrated by the almost universal acceptance and use of underground systems for collecting liquid wastes, with all of the sanitary advantages inherent therein.

Because the advantages of underground sewers caused their ready acceptance, it soon became only too apparent that the problem of disposing of the vast quantities of wastes collected by such systems was yet to be solved. Concentrations of raw sewage were discharged to streams and rivers or drained to marshy swamp-lands, creating gigantic cesspools and causing vile odors and air pollution in the areas nearby the points of disposal. The seriousness of the problem demanded that sanitary engineers quickly devise schemes for treatment to eliminate odors and protect the rivers and streams to which the treated effluent was discharged. It is safe to say that the technology of sewage collection and treatment has now reached the point where, with but rare exception, the air-pollution problems attendant upon collecting and disposing of liquid wastes have reached the vanishing point.

One exception is the discharge of particulate matter from equipment used to heat-dry or incinerate the organic solids or sludge removed from the liquid phase at sewage treatment plants. Devices which are presently used for drying raw or digested sewage sludge, or those which burn the organic material for disposal, are guilty of discharging particulate matter in stack effluents in quantities which usually exceed the standards set by local air-pollution-control authorities. Further design modification will be necessary before the heat-processing of sewage sludge is accomplished without excessive air pollution.

Collecting Refuse

To this day, no one has devised a feasible method for collecting combustible and noncombustible rubbish by any other means than surface vehicles. The practice of door-to-door collection of garbage, rubbish, and ashes is time-honored but expensive; yet there appears to be no satisfactory alternative for the collection of rubbish and ashes in the near future. Garbage and rubbish collection practices do not contribute to general air pollution even when such practices violate sanitary precepts. Nuisances may result and public health may suffer from the insanitary home storage of garbage and rubbish, as well as the use of open collection vehicles which litter the city streets; but these can scarcely be considered air-pollution problems. Present trends are toward the use of closed metal storage-containers at the home and collection in completely enclosed vehicles, which tend to consolidate the wastes for efficient transportation.

A practice which closely ties together the fields of garbage collection and that of sewage collection and disposal is the use of kitchen garbage-grinders. These devices are becoming increasingly popular as they eliminate the objectionable storing of garbage by discharging a ground pulp to the sanitary sewer where it is economically transported to the sewage treatment plant. Although the present high purchase price of kitchen garbage-disposal units will not completely justify the abandonment of present methods of garbage collection, the advantages to the housewife are so significant as to indicate widespread acceptance without the necessity for showing an economic saving.

Garbage Disposal

Garbage is presently disposed of by burial in landfills; incineration in combination with combustible rubbish; grinding to sewers through either large, centrally located grinding stations or individual home grinders; and feeding to hogs. Garbage reduction for grease recovery has been almost completely abandoned because of the lack of salvage value of the reclaimed grease, and the barging of garbage to sea has been discontinued because of the re-

*Presented at the First Semi-Annual Technical Conference of the Air Pollution Control Association at Los Angeles, California, November 4-6, 1954.

sulting beach pollution. A promising method which may serve to reclaim the fertilizing elements of garbage is that of composting; however this is not a fait accompli in the United States today, although some research is being done and small-scale operations conducted.

Even though the feeding of garbage to hogs has proved highly objectionable to people living within a few miles of garbage-feeding hog ranches, air pollution from this source is still a local or neighborhood problem. In the Los Angeles metropolitan area, objections to the offensive odors from hog ranches proved sufficient to cause the mass exodus of some 100,000 hogs from urban areas into mountainous areas near Saugus, a distance of some 60 mi. It is to be assumed that odors still prevail, but that the hog ranches now exist as "self-contained nuisances."

The grinding of garbage to sewerage systems at specially designed garbage-grinding stations is presently practiced at St. Louis, Mo., Lansing, Mich., and Marion, Ind. The prevention of odors and local air-pollution problems at garbage-grinding stations is a matter of good housekeeping, and moderate care in garbage handling will prevent serious odor-nuisance. The same holds true of composting operations where the decomposition occurs in closed digesters (Fig. 1). If open-field composting of garbage in windrows is practiced, precaution to prevent the compost piles from becoming anaerobic and releasing objectionable odors is imperative.

Collecting and Disposing of Rubbish

Rubbish, particularly its organic or combustible fractions, is the most perplexing enigma confronting the sanitary engineer in the field of refuse disposal. This is occasioned in part by the difficult task of collecting the enormous quantities which accumulate from present-day living activities, but is compounded by the fact that, once collected, these vast quantities must be either buried, burned, or in some manner, finally disposed of.

Even within the last decade it has been common practice to haul combustible rubbish to the nearest dump on the outskirts of town where it would be summarily piled and a match applied to it. The fact that this pile of rubbish (very often containing appreciable quantities of garbage) smoldered for several days was of little concern, provided the nearest neighbor was far enough away that the nuisance was tolerable. As cities grew, this practice of dumping was looked upon with less favor because areas suitable for such operations became too distant to reach economically, or (as occurs in metropolitan areas) the urban development of each city reached the outskirts of neighboring cities, virtually eliminating the possibility of finding sites that would not contribute to the discomfort of adjoining communities. In the Los Angeles area, this factor became manifest in 1948, at which time the Los Angeles County Air Pollution Control District caused the cessation of burning at open dumps.

A unique aspect of rubbish disposal in the Los Angeles area is one that has been inherited from our earlier days as a pueblo—the burning of combustible rubbish in the backyard in what are termed domestic incinerators. These are small single-chamber units, usually having a cast-iron grate and a screened smoke-stack. Although it must be granted that they provide a cheap alternative to the collection and disposal of combustible rubbish, the drawbacks of fire hazard and of air pollution outweigh any economic advantages. It has been estimated by some fire departments in the Los Angeles area that more than half of the calls for fire protection result from backyard rubbish burning.

The contribution of backyard incinerators to general air pollution is difficult to assess, but the reduction in visibility and local smoke and odor-nuisances caused by backyard burning are clearly evident. There is ample justification for the abandonment of backyard burning, solely on the basis of reducing fire hazards and eliminating the unpleasant and unfriendly relationships created among neighbors. An inexpensive rubbish-collection service, conducted in accord with good sanitation practices, is the best answer to the backyard incinerator; once homeowners have become accustomed to the convenience of collection service, there is little doubt that the backyard incinerator with its nuisances will be relegated to the same category as the outdoor privy.

The use of home barbecues need not be considered seriously, since the limited effect of burning very small quantities of wood and charcoal can scarcely be considered in the same light as backyard incinerators. In the Los Angeles metropolitan area, there are perhaps 1,500,000 backyard incinerators in present use, burning an estimated total of 2,500 tons of combustible rubbish daily and contributing about 50 tons of patriculate matter to the atmosphere, with another 50 tons estimated to be contributed by commercial and industrial single-chamber incinerators. In no other metropolitan area in the United States is such a practice condoned. It is almost universally accepted that rubbish should be collected and disposed of in such a manner as to eliminate pollution and fire hazards.

Municipal Incineration

Many of the metropolises in the United States have adopted large-scale incinerators as the answer to rubbish disposal. New York is rapidly expanding its present incinerator capacity so that ultimately all combustible rubbish and garbage will be burned; Chicago is beginning an incinerator construction program; Detroit burns much of its combustible rubbish and garbage in municipal incinerators; and many other cities burn all or part of the collected rubbish (Fig. 2). In the Greater Los Angeles area there are 10 municipal incinerators: two in Los Angeles, one each at Alhambra, Beverly Hills, Glendale, Huntington Park, Pasadena, Pomona, Santa Monica, and Signal Hill. The total burning capacity of these is about 2000 tons in a 24 hr. period. This represents about ⅓ of

the total requirement if all combustible rubbish in the metropolitan area were collected and burned.

Although municipal incinerators, ton for ton, discharge from ¼ to ⅓ of the particulate matter that is emitted from backyard single-chamber incinerators, it is still a moot point as to whether this degree of improvement is sufficient. From an air-pollution point of view, the most desirable method of waste disposal is that which does not utilize the atmosphere in any way for final disposal. Where wastelands are not available for landfilling, there can be no doubt that incineration is an appropriate engineering solution, as it reduces the volume of material to be buried to about 1/10 of the original volume and yields a filled land which has greater utility than completed sanitary landfills.

Landfills

Burying rubbish under controlled conditions which utilize earth-cover to prevent rat infestation and to minimize accidental fires is simple and inexpensive. Landfilling should be encouraged wherever wastelands are near enough to centers of population to permit inexpensive disposal and recovery of unusable properties for parks or other recreational uses.

Although incineration costs from $2.00 to $4.00/ton, whereas the cost of landfilling usually lies between $.50 and $1.00/ton, the selection of incineration is almost always made because the city is not deemed to be within economic hauling distance of landfill sites. There are engineering techniques, however, which extend the limits of economic haul. A disposal site which might prove completely infeasible under a scheme employing transportation to the site in collection vehicles may be reached economically by transferring the collected refuse to semi- or truck-trailers of 40 to 60 yd.^{3} capacity, and thence to the formerly remote site. This system, termed transfer-and-haul, is presently used in Chicago and Detroit, and is used in the Los Angeles area for transporting garbage to hog ranches 60 mi. distant. Some transfer-and-haul of rubbish in the Los Angeles area is done by private collectors when local landfills are not available (Fig. 3).

The transfer-and-haul philosophy can be adapted to rail transportation where the rail facilities reach areas suitable for extended landfilling or open burning. Problems that must be solved before rail transportation will prove satisfactory are:

1. the quick, simple loading of rail cars with rubbish,
2. the design and construction of rail cars having volumetric capacity and weight limitation specially adapted to light, bulky rubbish,
3. the quick, simple unloading of rubbish at the final disposal site, and
4. the possible integration of rail and truck hauling to minimize re-handling.

Salvaging Waste Materials

Many municipalities have embarked upon salvage ventures, particularly during war years, only to subsequently abandon salvaging and turn to other disposal methods. Present labor costs make separation procedures expensive, and often the cost of separation exceeds the value of the separated products. Some exceptions are: (1) the direct salvage of paper and cardboard for re-use in the paperboard industry, this usually being accomplished with fairly select materials from commercial establishments, (2) the separation of cans from noncombustible rubbish in the Los Angeles area, with subsequent re-use in the copper-mining industry, (3) the salvage of glass bottles and cullet, usually as a by-product of can separation, and (4) the utilization of garbage as feed for hogs.

It is generally conceded that salvage operations, being highly competitive and subject to the vagaries of the market, are best handled by intrepreneurs. An exception to this is found at Atlanta where tin-cans are salvaged after passage through the municipal incinerator and sold by the city to local foundries. Most salvage operations are materials handling and sorting procedures and do not contribute to air pollution. Where burning must be done, as in the processing of tin-cans, then some measure of control must be effected over the stack discharge.

The composting of garbage and combustible rubbish for use in soil conditioning may well be considered a salvage operation. In Holland, almost 250,000 T. annually of organic waste are returned to the soil through composting; and a few other European countries as well as New Zealand, South Africa, and a number of Asiatic countries have also utilized composting as a means of enriching agricultural lands for many years.

The natural wealth and fertility of soils in the United States, coupled with the widespread use of inorganic fertilizers, have lessened the demand for compost in this country. Sanitary engineers consider compost as serving to accomplish a dual purpose: effecting an economical disposal of organic refuse, and producing a usable soil amendment for increasing agricultural yields. Studies at the University of California (Berkeley) and at Michigan State University (East Lansing) have demonstrated that composting is feasible from an engineering consideration. Not so easily reconciled are the economic aspects of composting, for it still remains to be demonstrated that compost can be produced and sold in large enough quantities to justify the venture of municipalities into this yet unproven field.

Another scheme, as yet untested and perhaps more ephemeral than that of composting, is the possibility that combustible rubbish may be ground and discharged to sanitary sewers for transport to sewage-treatment plants, there to be removed and bacterially decomposed along with sewage sludge. Preliminary studies made by the Los Angeles County Sanitation Districts show that most components of combustible rubbish will decompose readily in anaerobic digesters, yielding methane gas and humus-like material.

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Control of Emissions From The Processing of Noncombustible Municipal Refuse*

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For over 35 years Los Angeles has been in an enviable position as compared to other large cities in the United States, as far as the disposal of noncombustible rubbish is concerned. This material, composed of tin-cans, bottles, glass, ashes, miscellaneous containers, rubbish, etc., is collected from the residential areas by city-operated trucks and dumped "as is" at contractor's salvage plants in easily accessible locations. It then becomes the bonded obligation of the contractor to dispose of same at no cost to the city. Presently the city collects approximately 275 12 yd.^{3} loads daily. This averages about 630 tons/day, of which 30% (after being subjected to special processing) is made salable by the contractor. The remaining 70% (about 440 tons daily) is entirely waste and is composed of ashes, broken crockery, finely broken glass, wash bowls, toilet bowls, plastic and cement materials, etc. A major investment is therefore involved in the ownership or leasing of nearby dump sites where this worthless residue may be deposited.

For the greater part of 35 years, the contractor either paid the city for the rubbish delivered to his plant or allowed the city free dump. The amount paid was determined by the use of a "yard stick," which took into consideration prices received for material salvaged and sold by the contractor from the city refuse.

This arrangement has saved the city hundreds of thousands of dollars and has been made possible solely through the development by the Los Angeles By-Products Co., of a unique product known as "Shredded Iron." This iron is produced by special processing equipment primarily for the copper industry, where it is used as a medium for the recovery of copper from low grade ore.

Actually, the discovery and development of a method to shred miscellaneous light gauge scrap-iron and iron containers, without compressing or baling, revolutionized the use of precipitating iron as a copper-recovery medium. This product, which is absolutely clean and free from contaminants, is now shipped in open gondola cars to all the major copper mines in the United States. Unfortunately, the demand for this material is very limited, as Southern California produces more light gauge sheet-iron materials than can be used by all of the domestic copper companies. Little expansion is possible, due to this limited market.

Although the opportunities for growth are restricted, it became apparent several years ago that new facilities would have to be provided to receive and process the noncombustible rubbish. It was estimated (and actual experience has proven this figure to be correct) that the construction of such a plant would involve an expenditure of approximately $1,500,000.

Not the least of the problems to be solved was the design and engineering of satisfactory dust-control systems. Air-pollution control with respect to this industry was virtually unknown. The research and development required before suitable equipment could be installed must be emphasized. To date, this preliminary work, together with the actual installation of the control apparatus, has already cost just under $500,000.

In order to fully describe the steps that have been taken to control smoke and dust emission in the newly constructed plant, the operation and flow of material through the old plant should first be considered.

One of the major problems was the handling of dirt and ashes contained in refuse. The receiving facilities for city noncombustible rubbish were wholly inadequate, not only from the standpoint of dust control, but also from the fact that storage bins were limited as to capacity, and space for maneuvering trucks was restricted. There were no partitions or dust-tight enclosures for individual truck dumping, nor was there any semblance of an exhaust system.

A dust problem existed during dumping operations, and difficulty was experienced throughout most of the handling system (Fig. 1 and 2). This was especially true where one conveyor discharged onto another conveyor or onto an elevator, where magnetic separation occurred, or where the cans were scoured in a rotary screen.

The former can incinerator discharged the dirtiest, densest, blackest smoke in the Los Angeles area (Fig. 3). This "bad boy" among incinerators was actually a rotary kiln where the cans were incinerated to remove labels, grease, tar, paints, organic matter and other adherents which would be detrimental to their use (Fig. 4).

As early as 1940, this company began experimental work in an attempt to find some method of controlling smoke and fly-ash emissions from the kiln stack. Equipment tested included a cyclone, a scrubber, a filter bag arrangement, and a high efficiency cyclone; and inasmuch as this latter test unit apparently offered the most desirable results, a high-efficiency-cyclone dust collector and fan were

*Presented at the First Semi-Annual Technical Conference of the Air Pollution Control Association at Los Angeles, California, November 4-6, 1954.

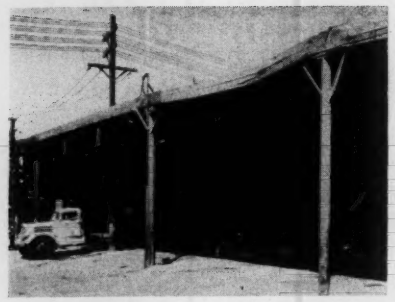


Fig. 1. Dumping Area in Old Plant, Now Dismantled, Completely without Dust-Control Facilities.

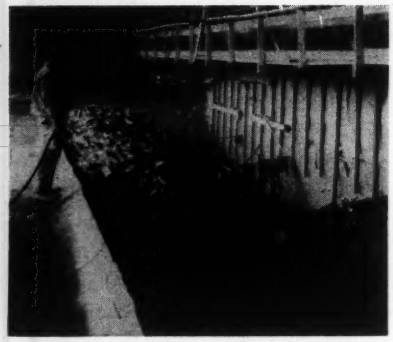


Fig. 2. Main Can Bin in Old Plant. Note Dust in Background.

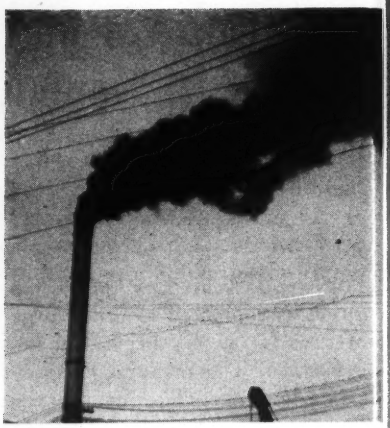


Fig. 4. Old Rotary Kiln "Discharged the Dirtiest Smoke in the Los Angeles Area"

installed in the spring of 1941. This alleviated but did not solve the problem. At the conclusion of the war, after further tests on various dust-collection units, 2 wet wash scrubbers were added, along with fans and accessory equipment. When the above apparatus was in operation, the gases from the rotary kiln were processed through the high efficiency cyclone and then through the 2 wet wash scrubbers connected in parallel, with each scrubber handling ½ the gas stream.

It was quite apparent that the rotary kiln, in conjunction with the collection equipment mentioned above, could not meet the requirements as set forth by the Air Pollution Control District. Smoke density, as gauged by the Ringlemann Chart, was generally in excess of the allowable limit, and the calculated loss of particulate matter was also in violation of air pollution regulations.

A multiplicity of tests were made to determine the nature of the pollutants. Invariably the results denoted similar composition, major constituents being aluminum oxide, iron oxide, and calcium oxide, and the remainder being other metallic oxides as well as volatile and combustible matter.

Investigations were conducted by various consulting engineers, one in particular being a study made by Mr. R. W. Rowen, Vice President of Nichols Engineering & Research Corporation, New York City. His conclusions regarding the operations of the rotary kiln and its collecting equipment might be summed up as follows: First,

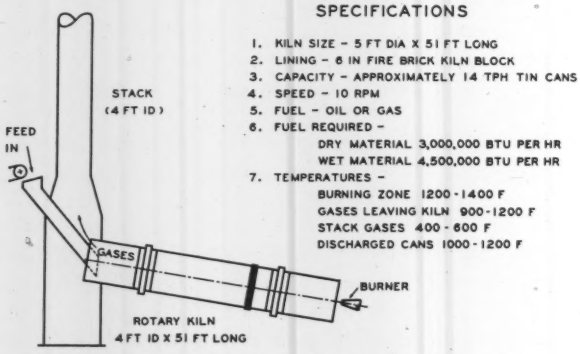

SPECIFICATIONS
1. KILN SIZE - 5 FT DIA X 51 FT LONG
2. LINING - 6 IN FIRE BRICK KILN BLOCK
3. CAPACITY - APPROXIMATELY 14 TPH TIN CANS
4. SPEED - 10 RPM
5. FUEL - OIL OR GAS
6. FUEL REQUIRED -
DRY MATERIAL 3,000,000 BTU PER HR
WET MATERIAL 4,500,000 BTU PER HR
7. TEMPERATURES -
BURNING ZONE 1200-1400 F
GASES LEAVING KILN 900-1200 F
STACK GASES 400-600 F
DISCHARGED CANS 1000-1200 F
STACK
(4 FT ID)
FEED
IN
GASES
BURNER
ROTARY KILN
4 FT ID X 51 FT LONG

Fig. 3. Old Rotary Kiln for Can Burning, Now Discarded.

there was insufficient draft at the upper or gas discharge end of the kiln to draw the required amount of air up through the kiln. Secondly, there was often insufficient temperature and time in which to complete the combustion of gases. The final result of all tests and experimentation showed conclusively that a new type of incinerator was mandatory.

The initial step was the fabrication of a small, crude pilot plant for burning the cans, the basic design being a radical departure from the rotary kiln principle. This pilot operation consisted of a standard apron conveyor, 5-ft. centers 30 in. wide, with solid, mild steel pans. Over this conveyor a rectangular firebox was constructed, inside dimensions being 48 in. by 30 in. Eight radiant-type burners were located in the roof of this firebox, and the heat was directed down onto the cans carried by the conveyor through the hot zone. As distillation of the adherents to the cans occurred, the objectionable gases rose to the roof of the firebox (located about 16 in. above the surface of the conveyor) and were immediately consumed in the intense heat (probably in the neighborhood of 2000°F.). Results were extremely encouraging. The cans were well burned and tests indicated that dust concentration was as low as 0.029 gr./ft.^{3} at 60° F. Just as important was the fact that the stack was absolutely clear—there was no visible color.

Combustion engineers were invited to inspect the pilot plant operation, and following several proposals a contract with an eastern manufacturer of incinerators was signed to construct a can incinerator capable of processing the entire plant production.

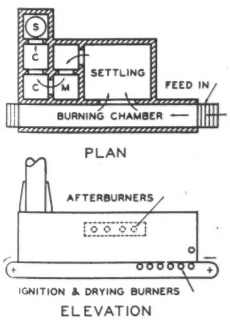
In the interest of brevity, we will disregard the many trials and tribulations which were present during the time of construction and subsequent period of testing. Simply note that construction required 1 year and that another 2 years of testing, experimentation, alterations, and additions were needed before the incinerator would not only meet the requirements of the Air Pollution Control District but also burn the cans properly. It is also interesting

that after about 6 months of testing the contractor left the job, and it was then our responsibility to design and make the necessary changes so that the incinerator would eventually operate to everyone's satisfaction. The description that follows is of the incinerator as it stands today, not just the original design, and includes all the modifications which were essential to successful performance.

As was true in the case of the pilot plant, the cans are fed onto a conveyor, which in turn carries the cans through a burning chamber (Fig. 5). This 60 ft.-conveyor is made up of 138 pans, is 5 ft. wide, and is carried on 12-in.-pitch chain. Meehanite metal was used in casting the pans (pans fabricated from Inconel sheets have also proven very satisfactory) and each pan contains over 600 holes of 7/16-in. diameter. A firebox is located under the first 22 ft. of conveyor travel and it is here that the burners provide the fire necessary to ignite the combustible material contained in or stuck to the cans. A total of 12 burners (6 from each side) fire into the center of the firebox, and the resultant fire and heat rise through the holes in the pans and start the combustibles burning.

It might be said that the burning chamber, 58 ft. long, 5 ft. wide, and 6 ft. high, serves 2 purposes: (1) As the cans travel through this chamber (speed is 20 fpm.) the paper, greases, paints, organic matter, etc., are given time to burn themselves out. (2) 10 additional burners, located in the area above the burning conveyor, supply enough supplemental heat to consume distilled volatile organics and eliminate smoke. After the gases leave the burning chamber, they pass through a flame port and then into a large settling chamber 13 ft. 6 in. square and 20 ft. high, containing a substantial baffle wall to improve settling action. The gases then travel through a brick checker wall, two 6 ft. square combustion chambers, and are finally discharged through a brick-lined stack.

The burning chamber, like the rest of the incinerator, is of standard construction—inner walls of firebrick and outer walls of red common brick. The walls of the burning chamber are flush with the outside edges of the conveyor and are built to provide a minimum of clearance between the top of the conveyor and the bottom course of brick. Normally, a bed of material approximately 2 ft.



SPECIFICATIONS

1. CAPACITY - 15 TONS OF CANS PER HOUR
2. CONSTRUCTION - STANDARD FIRE BRICK
3. BURNING CHAMBER - 5 FT W X 6 FT H X 58 FT L
4. SETTLING CHAMBER - 13 FT 6 IN SQ X 20 FT L
5. MIXING & COMBUSTION CHAMBERS - 6 FT SQ X 13 FT L
6. BRICK LINED STACK - 5 FT ID X 74 FT HIGH
7. PAN TYPE CONVEYOR - 5 FT W X 66 FT LONG
8. PAN MATERIAL - CAST MEEHANITE 1/2 IN THICK
9. CONVEYOR SPEED - APPROXIMATELY 10 FT/MIN
10. BURNERS -
    COMBINATION GAS & OIL FIRED
    26 AT 600,000 BTU/HR EACH WITH
    AUTOMATIC & TURN DOWN CONTROLS
11. TEMPERATURE (AVERAGE) (F)
    BURNING CHAMBER 1150
    SETTLING CHAMBER 1200
    MIXING & COMBUSTION CHAMBER 900-1200
    STACK 900

Fig. 5. Can-Burning Incinerator.

in depth is carried on the conveyor, and as the cans progress through the burning chamber there has been considerable abrasive wear on the side walls. To correct this situation, several courses (to a height of 18 in. above the conveyor) of carborundum brick have been installed and subsequent wear has been held to a bare minimum.

Temperatures range in the burning chamber from 1000° F. to 1300° F. and in the flame port from 1300° F. to 1350° F. The heat drops in the settling chamber to about 1200° F. and then enters the stack at slightly less than 1000° F.

There has been much discussion as to the merits of one of the original design features, specifically the location of the secondary combustion chambers following the settling chamber. It is the opinion of many that this sequence should be reversed so that more time and temperature could be applied to the gases after leaving the burning chamber and before entering the large settling chamber. As it is now, complete combustion of the gases must take place in the burning chamber and flame port, since upon entering the settling chamber the gases expand and the temperature drops. From an economical standpoint, it is not possible to reheat the gases in the succeeding combustion chambers in order to complete combustion.

Fuel for the burners is supplied through a combination oil or gas system which obviates having separate equipment for each type of fuel. Natural gas (which is available during most of the year) is pre-mixed with air, and the proper mixture is piped to each of the burners for firing. When the use of gas is restricted, kerosene distillate is heated in the converter equipment and the resulting vapor is fired in much the same manner, and through the same burners, as the natural gas. It has been found that the fuel requirement for satisfactory incineration is 8,000,000 to 11,000,000 Btu./hr., although this figure must be increased substantially during winter months when the cans are wet. The equipment has automatic features, is electrically controlled, and has flame rods on the burners to prevent explosions in the event of flame failure.

A number of tests were made on the stack of this incinerator, and a typical result showed the calculated loss from the stack to be 33.6 lb./hr. (Table I).

Now that the performance of the can incinerator was satisfactory, attention was turned to the layout of the

TABLE I
Typical Stack Test on Can Incinerator

Material incinerated	tin cans
Process weight	90,000 lb./hr.
Sampling station	⅔ up stack
Stack area	19.7 ft.^{2}
Stack temperature	1055° F.
Gas velocity	26.5 fps.
Flue gas volume	10,800 scfm.
Dust concentration	0.363 gr./ft.^{3}
Calculated loss	33.6 lb./hr.
Allowable loss	40.0 lb./hr.
Stack discharge (visual)	clear

remainder of the plant equipment, with emphasis on the incorporation of a successful and practical dust-control system. As explained earlier, there is hardly any operation, in conjunction with the processing of municipal noncombustible rubbish, which does not require some type of exhaust device.

In accordance with a new city contract, beginning January 1, 1951, ashes would no longer be segregated from the rest of the noncombustible rubbish, but instead would be mixed throughout the entire load. This meant that there would no longer be a separate plant for handling ashes—the new plant would have to be designed to cleanly handle the maximum volume of dirt and ashes. Exhaust hoods connected to suitable collecting equipment would have to be furnished at all locations where trucks are dumped, in the main can-bin basement where the rubbish is fed out of the bins, at all transfer points between conveyors and elevators, over the magnetic pulleys, and over all rotary screens. Where possible, a number of hoods have been grouped together and fed into a common header, thus minimizing the number of dust collectors in use. In 2 instances, 1 collector is employed for 2 separate systems; however, by means of an automatic damper control, only 1 system can be operated at any one time, thereby preventing overloading or a decrease in efficiency of the unit.

A dust filter or bag house was chosen as the most suitable collector for this application (Fig. 6). Each of the seven units installed have a rated capacity of either 35,000 cfm. or 40,000 cfm., the only difference being the size of the fan and motor, and arrangement of the filter sections. In all cases, cotton envelope-type bags are used with a total cloth area of 11,880 ft.²/baghouse. Every hour, each individual section is automatically shaken for a period of 3 minutes; however, even during the shaking cycle the filter

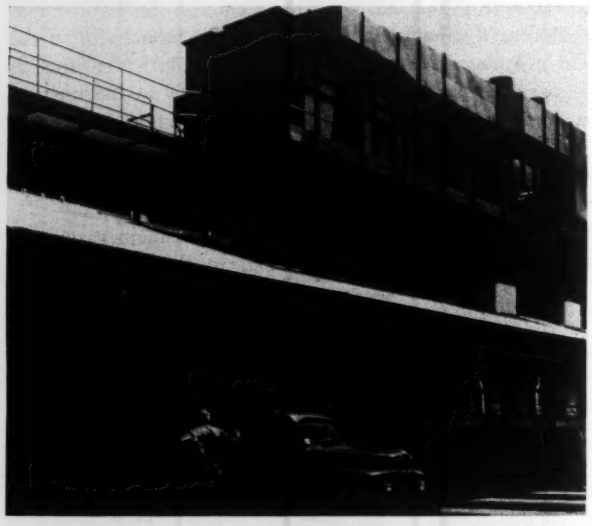


Fig. 6. City Truck, Dumping into Main Can Bin in New Plant. Note Dust-Tight Enclosures for Individual Truck Dumping and Dust Filters Above Bins.

Fig. 7. Main Can-Bin Basement Area in New Plant, Showing Hoods and Ducts Necessary for Dust-Free Operation.

remains in continuous operation. The filtered dust is collected in hoppers located underneath the bags, and these are unloaded each day by means of screw conveyors. Although the experience with these dust filters has been limited, they appear to operate on this type of dust very efficiently and to date the maintenance and repair has been slight.

As an example of design features, the dumping stalls where city trucks are unloaded have an air velocity across the face of the hood of 200 fpm. (Table II). This velocity has been very effective in preventing dust escaping to the atmosphere, even though a considerable cloud of dust is generated each time a truck is dumped. It was calculated that a volume of 10,000 cfm. would be required to provide the desired velocity, and inasmuch as there was the possibility of operating 6 or 7 hoods (out of a total of 13) at one time, it was decided that for this one exhaust system two 35,000-cfm. dust filters

TABLE II

Typical Dust Control System

Dust Filter	
	Type—4 section baghouse
	Gas volume at inlet—35,000 scfm.
	Filter area—11,880 ft.²
	Filter media—cotton envelope bags
	Shaking frequency—once per hour automatically
	Filter ratio—2.95 to 1
	Pressure drop—2.5 in. (wc.)
Duct Design	
	Total air handled—35,000 scfm.
	Velocity in main duct—3,500 fpm.
	Velocity in branch ducts—3,800 fpm.
	Exhaust hood face velocity—200 fpm.
	Pressure drop in duct—2 in. (wc.)

(Concluded on page 22)

Economics of Vapor Recovery From Storage Tanks*

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Petroleum products with subatmospheric vapor pressures may be stored in conventional cone-roof tanks. However, in many cases loss of product results from evaporation. This loss occurs during filling operations when vapors are forced out of the tank, and also as a result of tank breathing caused by changes in ambient temperature. The amount of loss from cone-roof tankage is a function of the vapor pressure of the stored product at the average liquid temperature, the average vapor volume in the tank, the tank diameter, the volume thruput, and the tank capacity.

There are several ways to reduce vapor losses from storage tanks. This paper deals with 3 methods: the installation of vapor recovery equipment, the replacement of cone roofs with floating roofs, and the installation of vapor-balancing facilities.

To compare the economics of these 3 methods of vapor control, 3 hypothetical cases were assumed. These 3 cases are not based on any one company's installations but reflect extremes of conditions to straddle the economics of control devices.

In Case 1, 50 tanks of 1000-barrel capacity each were considered with a thruput equivalent to 40 turnovers/tank/year. Case 2 consisted of ten 100,000-barrel tanks with the same 40 turnovers/tank/year. Case 3 consisted of ten 100,000-barrel tanks with no thruput. This last case was picked to determine the effect of filling losses on the economics of each installation. In each of these 3 cases, 2 stocks were considered: a fairly low vapor-pressure stock with 1.5 psia under the operating temperature, equivalent to JP-4 jet fuel; and a 6.2 psia true vapor-pressure stock, equivalent to motor gasoline.

In each case, it was assumed that the tanks were arranged 5 to a row, spaced 3 tank diameters apart, center-to-center. The 1000-barrel tanks were assumed to be 18 ft. high, 20 ft. in diameter and to have a maximum temperature rise of 20° F./hr. The 100,000-barrel tanks were assumed to be 40 ft. high, 135 ft. in diameter, and to have a maximum temperature rise of 14° F./hr. The vapor-loss calculations were based on tanks half full on the average.

Vapor Recovery

Vapor recovery, as used here, refers to a system of gathering the vapors discharged from cone-roof tanks and processing these vapors for the recovery of condensable hydrocarbons by means of liquefaction. This requires relatively extensive processing equipment, the most common method involving compression, cooling, absorption, heating, stripping, and final condensation by cooling. Also, this equipment must be designed to operate under conditions of wide fluctuations in vapor flow rates from tankage, and of varying composition of the vapor. The recovered liquefied hydrocarbon can be either stored in relatively small volume, pressure storage vessels or used as feed stock for further processing.

In operation of the vapor-recovery facilities, vapors from each tank are gathered by means of light-weight ducts, pass through a pressure-control valve into the main gathering header, and are drawn into the suction of a compressor. After compression to 50 psig, the vapors are discharged into the absorption column where they are absorbed in circulating lean oil. The noncondensables, consisting of air with some propane, are discharged from the top of the column as fuel gas. The lean oil, enriched with the absorbed vapors, passes from the bottom of the absorber to the stripping column, where the oil is stripped of the vapors by steam. The lean oil recirculates to the absorber and the recovered hydrocarbons from the top of the stripper are cooled and condensed.

In designing vapor-recovery facilities, it should be noted that although almost identical equipment is required in the cases of the 2 stocks, cone roof tanks containing 1.5 psia stock would have a vapor space in the explosive range most of the time. The average concentration of hydrocarbons is 8% in the vapor from this stock, as compared to 25% in the vapor from 6.2 psia stock. To eliminate the explosive hazard in the compressor, it would be necessary to inject sufficient natural gas at the compressor suction to raise the hydrocarbon content of the va-

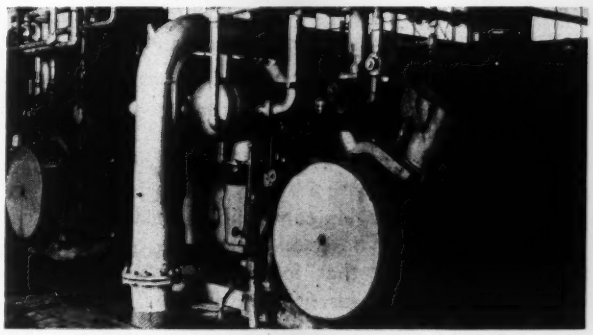

Fig. 1. Vapor Recovery System—Product Storage: The compressors shown pull vapors from tanks, compress these vapors to 50 lb./in.² pressure and discharge to a conventional adsorption system.

*Presented at the First Semi-Annual Technical Conference of the Air Pollution Control Association at Los Angeles, California, November 4-6, 1954.

†Prepared by the Technical Subcommittee of the Western Oil and Gas Association.

por of the 1.5 psia stock to 25%. The installations considered here are equipped with such precaution. However, although the explosion hazard in the vapor space of each tank could be reduced by installing a gas-blanketing system, it is better practice to store the 1.5 psia stock in floating-roof tanks.

The installation of vapor-recovery facilities would require a capital investment of $100,000 in Case 1 and $235,000 in Cases 2 and 3. In Case 3, provision is made for the eventual emptying of the tanks and subsequent refilling, a situation then paralleling Case 2. These estimates are based on not providing vapor balancing between tanks and no gas blanketing of tanks. It does not include the land value of the site, but does provide for the extension of existing utilities to the area. The facilities require an operator, and in addition, steam, electricity, and cooling water as utilities. The total annual operating cost including maintenance, insurance, taxes, and interest, but excluding amortization, is $33,540 for Case 1, $49,190 for Case 2 and $41,450 for Case 3.

Based on values of recovered gasoline at $0.10/gal. and fuel gas at $0.20/therm, Case 1 loses $28,710 a year before income taxes and amortization when the stock has 1.5 psia vapor pressure and $15,810 a year with 6.2 psia stock. Similarly, Case 2 returns an annual profit before taxes and amortization of $9,220 for 1.5 psia stock and $173,580 for 6.2 psia stock. Case 3 loses $29,950 a year with 1.5 psia stock but makes an annual profit of $810 with 6.2 psia stock.

Conversion to Floating Roofs

The installation of floating roofs as a means of reducing losses of hydrocarbons from petroleum storage tanks is one of the earliest conservation measures practiced. These roofs float on the surface of the stored liquid and have several advantages. The most important advantage, besides the obvious one of reducing the vapor loss, particularly when the turnover rate in the tank is high, is the minimized fire and explosion hazard due to elimination of the vapor space. A further advantage of floating roofs is the reduced corrosion by sour crude and other sour petroleum products.

Floating-roof tanks consist of a steel deck riding directly on the oil, covering all but a 12-in. or smaller ring at the edge of the deck. The ring is closed off by a seal which consists of a flexible metal shoe held out against the side of the tank and connected to the floating deck by a vapor tight, fire-resisting, flexible material.

The capital investment required to convert the 50 tanks considered in Case 1 to floating roofs is $400,000. Cases 2 and 3 required a capital investment of $450,000 for floating roofs. The annual operating cost of these floating roofs above that for cone-roof tanks includes maintenance, taxes, insurance, and interest, and amounts to $24,000 for Case 1 and $27,000 for Cases 2 and 3. The reduced hydrocarbon loss (using $0.10/gal. as the value of the gasoline saved) yields a net loss, before taxes and without amortization, of $23,100 a year for 1.5 psia stock in Case 1 and $18,740 a year for 6.2 psia stock. In Case 2 the recovered gasoline produces net profits of $10,310 a year with 1.5 psia stocks and $182,270 with 6.2 psia stocks. Floating roofs installed in Case 3 lose $19,790 a year on 1.5 psia stocks and yield a profit of $1,930 a year on 6.2 psia stocks.

Vapor Balancing

The simplest type of vapor-balancing facility consists of a network of vapor lines interconnecting the vapor spaces of all tanks. Under the most favorable conditions of perfectly balanced pumping, with the input rate equal to the output rate, it is possible to eliminate all filling losses. However, control of losses caused by unbalanced pumping and breathing requires variable-space vapor storage with a capacity equal to the volume of the maximum breathing plus unbalanced pumping. It is necessary, of course, to so design the system that the static head in the vapor storage plus the pressure drop through the lines at maximum vapor flow is less than the pressure setting of the relief valves on the liquid storage.

With regard to vapor-balancing systems, the primary operating consideration is the potentially adverse effect of the interchange of vapors between tanks storing different stocks. As examples, butane from high-vapor-pressure stocks could cause an unacceptable increase in the vapor pressure of stocks with lower-volatility specifications or vapors from high-sulfur stocks could be detrimental to sweeter products. Other considerations include the economics of the situation, the size and geography of the tanks or tank farm, and the amount of supervision available.

It should be noted that with the exception of possible contamination by inter-transfer of vapors, the vapor pressures of the stocks have no effect on the design, since there is no transfer of gases between the tanks and the atmosphere.

The conditions specified for Case 1, in which the pump-out rate is equal to the input rate, are such that a simple interconnecting pipe system would recover only the filling losses which amount to approximately 30% of the total loss. The addition of a vapor tank prevents all vapor losses. The vapor spaces of all tanks are connected by lightweight 2-in. ducts to 6-in. headers which are connected in turn to a variable-space, low-pressure, gas holder of 20,000 ft.^{3} total capacity. The estimated cost of this installation is $100,000, of which $25,000 is for the vapor tank.

While this particular tankage arrangement may not be practical, similar systems with fewer tanks are common. In such installations, the vapor-tank capacity is directly proportional to the unbalanced pumping rate and the maximum breathing. Maximum breathing is determined by the maximum diurnal temperature range and the average vapor space in the storage tanks. Line sizes are set by the maximum rate of both the diurnal temperature change and pumping.

In Case 2 the specified operating conditions of a pump-out rate twice the input rate are such that a simple interconnecting vapor-line system would recover half of the filling losses, or approximately 42% of the total losses. To prevent all vapor losses requires the addition of 1,800,000 ft.^{3} of vapor storage, composed of twelve 150,000-ft.^{3} vapor tanks. The total installation requires a capital investment of approximately $800,000.

The operating conditions of Case 3 are such that all losses could be eliminated by installing small-diameter interconnecting piping and a 20,000-ft.^{3} vapor tank. However, such an installation would have no practical value in an oil refinery, because storage tanks seldom stand idle for long periods. For this reason the vapor-balancing system would be designed, as in case 2, to permit future use of the storage tanks.

In all 3 cases, then, the facilities were based on recovery of all vapors. The annual operating costs, including maintenance, insurance, taxes and interest amounts to $6,000 for Case 1, and $48,000 for Cases 2 and 3. Based again on a gasoline value of $0.10/gal., the savings of vapor are such that the net margin before income taxes and without amortization amounts to a loss of $1,170 a year in Case 1 with 1.5 psia stock and a profit of $12,860 in Case 1 with 6.2 psia stock. In Case 2 the net margin is an annual profit of $10,410 with 1.5 psia stocks and $195,290 with 6.2 psia stocks. In Case 3 the net margin is an annual loss of $36,500 with 1.5 psia stocks and an annual loss of $1,860 with 6.2 psia stocks.

Comparison of Methods of Recovery

Of the 3 methods of control, the installation of vapor-recovery facilities requires the lowest capital investment, particularly in the case of the larger tanks. These facilities, however, require operating manpower, utilities, and a higher maintenance cost which offset the lower investment.

Due to the explosion hazard, use of cone-roof tanks, either with or without vapor-recovery facilities, is not recommended for the storage of the 1.5 psia vapor-pressure stock unless gas blanketing of the tanks is employed. For this reason, floating roofs are preferable for this stock.

In controlling the small tanks, the installation of floating roofs requires the largest capital investment of the 3 methods. However, on larger tanks this method is considerably cheaper than the vapor balancing system and has the advantage of being less dependent on the proximity of neighboring tanks. The vapor-recovery and vapor-balance systems recover essentially all of the vapors, while there is a small but definite loss of vapor to the atmosphere from floating roofs.

The use of a vapor-balancing system may be limited by contamination due to inter-transfer of vapors. Furthermore, when adopted only for tanks storing low-vapor-pressure stocks, gas-blanketing facilities may have to be provided to insure a nonexplosive atmosphere within the system.

The basic data and economics are shown in Table I for all cases, systems and operating conditions. The preferred system for each case is carried through to payout time after income tax. Broad generalizations which may be drawn from the table are as follows:

TABLE I

Economics of Vapor-Loss Reduction From Storage Tanks

	Case 1						Case 2						Case 3						Rule 56
Number of Tanks	50						10						10						218
Capacity of Each Tank	1,000						100,000						100,000						6,522,000 (Total)
Turnovers per Year	40						40						0						.....
True Vapor Pressure of Stock, psia	1.5			6.2			1.5			6.2			1.5			6.2			1.5—6.2
Method of Recovery	Vapor Recovery	Floating Roofs	Vapor Balance	Vapor Recovery	Floating Roofs	Vapor Balance	Vapor Recovery	Floating Roofs	Vapor Balance	Vapor Recovery	Floating Roofs	Vapor Balance	Vapor Recovery	Floating Roofs	Vapor Balance	Vapor Recovery	Floating Roofs	Vapor Balance	Various
Capital Investment, $	100,000	400,000	100,000	100,000	400,000	100,000	235,000	450,000	800,000	235,000	450,000	800,000	235,000	450,000	800,000	235,000	450,000	800,000	5,050,000
Recovery, Bbl. per Day	3.15	0.6	3.15	12.3	3.43	12.3	38.1	24.34	38.1	158.7	136.5	158.7	7.5	4.7	7.5	30.1	18.87	30.1	532
Value, $/Year	4,830	900	4,830	17,730	5,260	18,860	58,410	37,310	58,410	222,770	209,270	243,290	11,500	7,210	11,500	42,260	28,930	46,140	815,410
Operating Cost, $/Year:																			
Labor	21,900	.....	.....	21,900	.....	.....	21,900	.....	.....	21,900	.....	.....	21,900	.....	.....	21,900	.....	.....	
Utilities	4,140	.....	.....	4,140	.....	.....	9,660	.....	.....	9,660	.....	.....	1,920	.....	.....	1,920	.....	.....	
Maintenance[a]	3,500	8,000	2,000	3,500	8,000	2,000	8 230	9,000	16,000	8,230	9,000	16,000	8,230	9,000	16,000	8,230	9,000	16,000	101,000
Insurance & Taxes, 2%	2,000	8,000	2,000	2,000	8,000	2,000	4 700	9,000	16,000	4,700	9,000	16,000	4,700	9,000	16,000	4,700	9,000	16,000	101,000
Interest, 2%	2,000	8,000	2,000	2,000	8,000	2,000	4,700	9,000	16,000	4,700	9,000	16,000	4,700	9,000	16,000	4,700	9,000	16,000	101,000
Total	33,540	24,000	6,000	33,540	24,000	6,000	49,190	27,000	48 000	49,190	27,000	48,000	41,450	27,000	48,000	41,450	27,000	48,000	303,000
Operating Loss $/Year	28,710	23,100	1,170	15,810	18,740	.....	.....	.....	.....	.....	.....	.....	29,950	19,790	36,500	.....	.....	1,860	
Operating Profit $/Year	.....	.....	.....	.....	.....	12,860	9,220	10,310	10,410	173,580	182,270	195,290	.....	.....	.....	810	1,930	.....	512,410
Depreciation, 10%			10,000			10,000	23,500			23,500				45,000			45,000		505,000
Loss after Depreciation $/Year			11,170			.....	14,280			.....				64,790			43,070		.....
Profit after Depreciation $/Year			.....			2,860	.....			150,080				.....			.....		7,410
Loss after Inc. Taxes (45%) $/Year			5,030			.....	6,430			.....				29,160			19,380		
Profit after Inc. Taxes (45%) $/Year			.....			1,290	.....			67,540				.....			.....		3,335
Add: Depreciation $/Year			10,000			10,000	23,500			23,500				45,000			45,000		505,000
Available for Payout[b] $/Year			4,970			11,290	17,070			91,040				15,840			25,620		508,335
Payout Years			Infinite			8.9	25.5[c]			2.6				Infinite			236[d]		10
Capital returned (at end of 10 yrs.)			49,700											158,400					
Capital unreturned			50,300											291,600					

(a) Floating roofs and vapor balance 2%, vapor recovery 3½%.

(b) Ten years only.

(c) Ten years, plus $\frac{235,000 - 170,700}{.45\ (9,220)} = 25.5$

(d) Ten years, plus $\frac{.45\ (1,930)}{450,000 - 256,200} = 236$

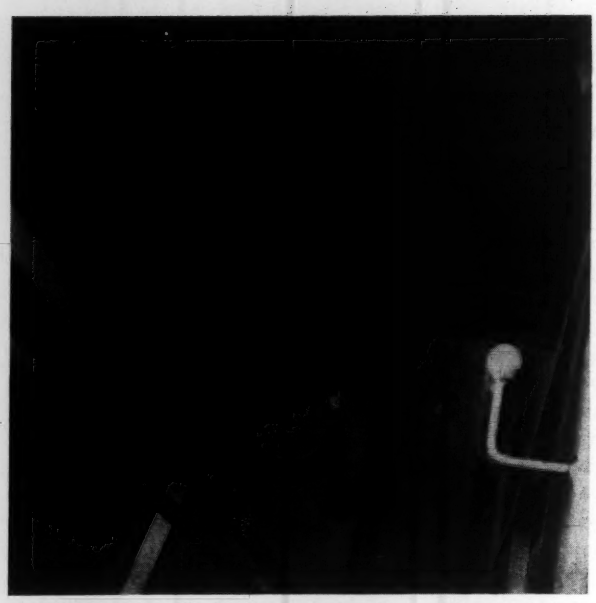

Fig. 2. Floating Roof Tank—Product Storage: This view from the top shows the roof at an intermediate point in the tank.

1. Vapor balance is the preferred system for small tanks containing gasoline.
2. For large tanks, vapor recovery is favored over floating roofs when a substantial number of tanks are involved.
3. For large tanks, floating roofs are favored when only a small number of tanks are involved.
4. High turnover favors vapor recovery over floating roofs, and vice versa.

The variation in the advantages of vapor recovery and floating roofs is of course due to the fact that, with floating roofs, the capital expenditure and the operating expense per tank is entirely independent of the number of tanks. On the other hand, the capital and operating cost of vapor-recovery systems per tank decreases as the number of tanks is increased.

Rule 56

In April of 1953, the Los Angeles County Board of Supervisors passed Rule 56 which required that all tanks containing material having a true vapor pressure of 1.5 lb. or higher at the operating temperature be equipped with floating roofs, a vapor-recovery or a vapor-balance system. Tanks were divided into 4 classes, depending upon the size of the tank and the type of petroleum product stored. Completion times were specified as follows:

Class 1—Containing cracked material, 400,000 gal. and over, completion February 1, 1954.
Class 2—Cracked material, 40,000 to 400,000 gal., August 1, 1954.
Class 3—Straight run, 400,000 gal. and over, February 1, 1955.
Class 4—Straight run, 40,000 to 400,000 gal., May 1, 1955.

At the time the rule was passed, there were 421 tanks (66%) in compliance, with capacity of 20,262,000 bbl. (75.6%);and there were 218 tanks (34%) not in compliance, with capacity of 6,522,000 bbl. (24.4%). (Data from 9 companies having 91.4% of the capacity in Los Angeles County.)

At the present time, there is complete legal compliance with the rule; in fact, the entire program is substantially complete, six months ahead of schedule.

It is not within the scope of this paper to present details on the many and varied installations which were made as a result of the passage of Rule 56.

The installation of floating roofs was the most common method of bringing tanks into compliance for the reason that many of the tanks were in small, isolated groups and therefore not well adapted to vapor recovery. In some cases, vapor-balance systems were installed on sizeable groups of large tanks where the turnover was relatively low. In cases where vapor-recovery systems were already in existence, small tanks were connected to the system. Several complete vapor-recovery systems were installed by small refineries.

Over-all economics covering the application of Rule 56 were estimated from information furnished by the 9 companies participating in the Technical Subcommittee work. Total capital expenditures were $5,050,000 and total gasoline recovery was estimated at 532 bbl. With gasoline valued at $0.10/gal., and with operating costs based conservatively upon the assumption that all installations were either floating roofs or vapor balance, a payout time of 10 years after income taxes is indicated.

It will be noted that the payout time for Rule 56 falls within the range indicated by the hypothetical cases. This would be expected since the average tank size is 30,000 bbl., average turnovers per year probably lie in the range of 10 to 20, and average true vapor pressure would be between 1.5 and 6.2 pounds; and all of these lie within the ranges assumed for the hypothetical cases. As a matter of fact, the payout time, while not attractive,

(Concluded on page 63)

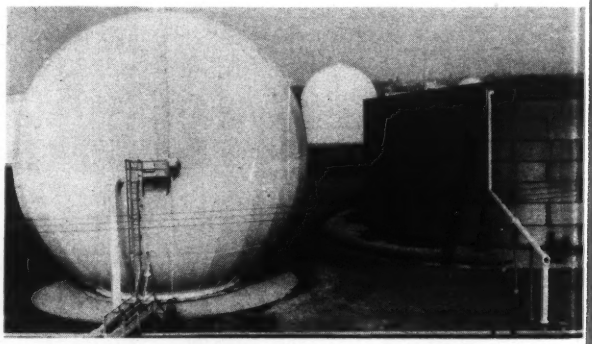

Fig. 3. Vapor Balance System—Product Storage: Gasoline products entering the cone roof storage tanks displace hydrocarbon-laden air which is "breathed" into the spherical tanks through the connecting piping. Temperature changes also cause vapors to flow in (or out) of the vaporspheres, where a rubber and nylon diaphragm maintains even pressure. Thus no vapors are permitted to escape to the atmosphere. In this installation three 150,000 cu. ft. vaporspheres service 16-80,000-bbl. storage tanks. Two 100 hp. compressors, instrumentation, and piping complete system.

Fume Filters For The Roofing Industry*

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Roofing plants in Los Angeles County had 3 major problems to handle in order to comply with regulations set up by the Air Pollution Control District.

Dust Collection

The first problem involved the discharge of dust into the atmosphere, a relatively easy problem. Baghouses were installed to collect dust discharged from filler heating systems, at dust pick-ups on the roofing machines, and at a number of points where dust is created at conveyor discharges, charging hoppers, etc. Baghouses are standard equipment, and the only engineering required is that involved in connecting them to existing equipment and locating them in out of the way areas.

Asphalt Blower Fumes

The second problem, which also was not too difficult, involved the discharge of fumes from asphalt-blowing operations. This was handled through the use of reasonably standard water wash-towers and fume incinerators. The incinerators are similar to those used in the coffee-roasting industry and other places where combustible discharges in small quantities must be treated. Gas volumes from the blowing stills are about 4000 cfm., and correction installations cost about $8,000 to $10,000. A typical installation consists of a water wash-spray in the lower portion of a venting stack, with the fume incinerator installed in the stack just above the wash section.

Asphalt Saturator Fumes

The major, and most complicated, problem concerned fumes generated when roofing felt is saturated with hot asphalt. The process primarily consists of applying the asphalt by spraying or by dipping a special paper called roofing felt. The paper contains 5 to 10% moisture which is immediately flashed upon contact with asphalt at 400° F. Steam distillation takes place on the surface of the sheet, and light oils are evaporated from the asphalt. The oils recondense a very short distance from the asphalt surface, and in so doing form an aerosol. The droplets are submicron size, so that they are suspended in the air like smoke particles and have the appearance of white smoke.

For many years, everyone was of the opinion that saturator fumes were primarily water vapor plus a very small quantity of hydrocarbons. Asphalt is produced by blowing air through petroleum residuum for 5 to 10 hr. with the material at approximately 450° to 500° F., and for that reason no one realized that light ends could still be flashed off. However, analysis of the fumes indicates that they are an aerosol of oil with characteristics similar to SAE No. 20 lubricating oil and that no condensed water vapor is present, since the relative humidity is about 28%.

Three roofing companies combined their efforts to develop a collecting method which would be satisfactory to the Air Pollution Control District and still not be prohibitive in cost.

The problem resolved into two parts: the first, coralling the fumes (hood design) and conveying them to some treating equipment; and second, collecting or removing the fumes.

Hood Design

Access through the hoods had to be provided for threading the paper through the saturators and arrangements had to be made for continuous observation of saturating conditions. Three different hood designs are being used. One requires the installation of sliding doors across the front of the saturator. The second was arranged so that a small sheet-metal building which housed the operation, became the fume hood. The third design is typical of those used in eastern plants, in which the hood goes to the floor at the back of the machine but stops approximately 6 ft. off the floor at the front. The main disadvantage of the third design is that very large volumes of air must be handled to properly ventilate the operating area, since it is necessary to maintain a velocity of about 150 ft./min. across all openings if fumes are to be kept completely within the hood.

Fume Collection

Preliminary studies with the aerosol covered all commercially available types of filters, water wash-units, and scrubbers. No single treating unit was found to satisfactorily break up the aerosol and collect enough of the oil. The 3 solutions which were finally developed required combinations of units, and they all remove at least 80% of the hydrocarbons present.

It was found necessary to do 3 things to satisfactorily handle the fumes: first, the vapors must be cooled from about 250° to below 110° F. so that condensable gases can be removed; second, the aerosol must be reduced to droplets of oil; and third, the oil and associated water must be collected.

The simplest, least expensive arrangement consists of a collecting hood over the saturator through which approximately 20,000 cfm. of air and fumes are discharged to a long, almost horizontal, section of duct. In the

*Presented at the First Semi-Annual Technical Conference of the Air Pollution Control Association at Los Angeles, California, November 4-6, 1954.

duct, water is sprayed at 40 to 60 lb. pressure. The combination of water-saturated air, oil mist, and liquids is discharged into a collecting chamber at the far end of the duct. One installation serving a roofing machine has a duct approximately 200 ft. long and uses 28 high-pressure sprays. The collecting chamber is a vertical, circular tank of about 15,000 gal. capacity with a stack on top and a water drain at the bottom for recycling. Oil is periodically pumped off at higher elevation and burned as fuel oil. This type of operation requires the addition of both wetting agents and anti-foam compounds to bring the efficiency within acceptable limits.

Another type of installation, using a similar hooding, discharges the fumes through a baffled water wash-unit, using a low-pressure spray and only enough water to reduce fume temperatures to about 100° F. The fumes are then discharged into a baghouse containing 12-20 in.-diameter, 12 ft. long cylinders made of ⅛-in. thick piano felt. The felt in this case does not act as a filtering medium but provides a means of breaking the aerosol. Collected oil runs down the inside of the bags, while the fumes that pass through the cloth enter tangentially into a cyclone chamber at the base of a discharge stack. The cyclone knocks out large drops of oil which are carried over from the cloth surface. This type of installation requires no additives but operates against a back pressure of 10 to 12 in. of water. The efficiency of these units is about 85%, and based on the readings made by the Air Pollution Control District inspectors the opacity of the discharge is in the range of 10 to 20%.

A third solution of the problem was found by combining a roto-clone washer, an impingement filter and an electrostatic precipitator. This is the most efficient, but also the most costly type of installation. The fumes go from a collecting hood to the roto-clone, then through the fan and impingement filters to the electrostatic precipitator.

Comparison of Costs

So that the different methods can be compared, the following figures are offered. Installations using high-pressure sprays and a long duct cost from $20,000 to $35,000 per saturator. Fume-handling equipment using a felt baghouse costs approximately $25,000. An installation using the roto-clone and electrostatic precipitator required an investment of approximately $46,000. These costs include the saturator housing, duct work, fan, and fume-treating equipment. Each of the installations has its characteristic maintenance and operating problems.

Common to all is the problem of keeping the duct work and housing sealed against oil leaks. This is more difficult than would first appear, since the oil passes through the finest cracks. Wherever possible the connections are welded, as bolted construction using gaskets will eventually leak.

It is estimated that the combined operating and maintenance costs for each of the units will run between $1,000 to $2,000/yr. The high-pressure spray systems require power for pumps, additives to the water, and normal maintenance due to corrosion. The baghouse units require dry cleaning of bags every 6 to 8 weeks and replacement of bags once or twice a year. The electrostatic precipitator units probably have the lowest operating costs, but wires in the 1800 v. precipitators must be completely replaced once or twice a year and the depreciation charges are about twice those of other units.

The oil collected from each saturator amounts to about 1 bbl./day. This is usually disposed of by mixing with plant fuel oil. It can be seen that the value of material collected does not nearly compensate for the cost of operating the filters. There are presently 15 roofing-felt saturators in operation in Los Angeles County, each of which has been equipped with a fuel filtering unit at an approximate total investment of ½ million dollars.

These units are removing a total of approximately 6,000 lb./day of oil which would normally be discharged to the atmosphere. Compared to the discharge of some 800 tons/day of hydrocarbons which result from the use of gasoline in automobiles, air pollution from roofing operations is insignificant; and even before filters were installed, it was relatively slight.

(Continued from page 16)

Control of Emissions from Municipal Refuse

should be installed. Duct velocities have been computed at between 3500 fpm. and 4000 fpm., with a pressure drop across the entire duct system of from 4 to 5 in. (water column). The dust filters in operation show a pressure drop of about 3 in., and on the basis of 11,880 ft.² filter area, the filter ratio of this equipment is 2.95 to 1. Each exhaust system has been engineered, as nearly as possible, to duplicate this performance (Fig. 7).

As one might surmise, this disposal operation and service is most unique. It follows that much of the engineering work, whether it be on dust control, shredders, or magnetic equipment, had to be pioneered by our personnel. Generally, there were no precedents, and many of the final results were obtained by the simple procedure of trial and error. However, in the field of air pollution, great assistance was offered by the entire staff of the County of Los Angeles Air Pollution Control District, as well as by Mr. R. W. Rowen and Mr. S. J. Horrell, to only mention a few; and for their fine contributions we are indeed grateful. It is evident that diligence and the application of sound engineering principles have aided in the reduction of air contaminants in this plant.

Smog Control In The Steel Industry*

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Simply stated, smog control in our industry involves the problem of collecting smoke, dust, and fumes generated in the process of making steel castings. However, if it were as simple to solve as it is to state the problem, there would be little interest in this paper.

There are several operations in every steel foundry which generate smoke and dust but none that I am aware of that generate noxious fumes. Most of these operations were under control before the Los Angeles County Air Pollution Control Act was adopted (at least to the extent of clearing the working area) and in most cases, collectors of various designs were in use. However, no one had ever attempted to collect the smoke and dust resulting from the melting furnace operation.

This paper will deal mainly with the furnace problem, but we shall also briefly describe our methods of controlling air pollution from other operations.

Pattern and Carpenter Shops

Practically all machines used in our woodworking shops are equipped with built-in dust hoods and are exhausted through cyclone collectors. Branch pipes run to traps which remove large pieces of wood and prevent the cyclone from clogging. Air velocities of 4,000 cfm. in branch pipes pick up the dust and velocities of 3,000 cfm. in the main duct carry the material to the cyclone in a satisfactory manner. The refuse is either burned in approved incinerators or hauled away to a dump and buried.

Cleaning Room

The processes producing dust or smoke in the Cleaning Room are:

1. Grinding
2. Shot-blasting
3. Annealing and heat treating

Annealing oven operation does not pose much of a problem. Practically all these ovens burn natural gas, combustion is complete and the exhaust gases are clear and composed mainly of carbon monoxide and carbon dioxide. The ovens are equipped with stand-by oil burners for use during extreme cold spells in winter when gas shortages compel us to use oil. Care must then be taken to avoid incomplete combustion and black smoke.

Grinding and shot-blast operations generate the same kind of dust, consisting of finely divided silica, powdered iron, and emery dust. Our industry has collected these dusts for years as a protection against the silicosis hazard.

Both wet collection systems and bag-house installations are in use and function well. Disposal of sludge from wet systems is a messy problem and, for that reason, bag house installations find more favor.

The advent of air-pollution control called only for inspection to make certain the installations were adequate in size and functioning properly so that exhaust stacks met the requirements of the law.

Core-Making and Molding Departments

The processes which need attention in the Core-Making and Molding Departments are:

1. Sand reclamation
2. Core ovens
3. Pouring operations

Some smoke is emitted in pouring operations, but it is a very small amount and there is no practical way to collect it. Much of what looks like smoke is steam coming from the backing sand of the molds as heat is transferred from the cooling steel to the mold itself.

Core ovens are gas-fired and present no problem except that part of the linseed oil used in making cores is oxidized and passes out the stacks. However, since our total use of core oil is only about 5 bbl./mo., this is no problem.

Sand reclamation starts at the shake-out grates which are hooded and exhausted into a closed system. Hammer mills, screens, cooling towers, and elevator boots are all exhausted. Both wet and dry collection systems were in use at the time the Air Pollution Control Act became effective, and again it was a question of checking the adequacy and efficiency of the units in operation.

Melting Department

Our main problem was encountered when we attempted to control dust and fumes from our electric melting furnaces. The 4 furnaces involved are arc furnaces ranging in size from 1 ton to 6 ton charges.

These furnaces tap at temperatures around 3000° F.

TABLE I
Particle-Size Distribution of Electric Arc-Furnace Dust

Size Range Over 325 mesh	Weight %	Cumulative %
25 - 44 μ	11	11
11 - 25 μ	7	18
3 - 11 μ	64	82
Below 3 μ	18	100
	Less than 0.2	

*Presented at the First Semi-Annual Technical Conference of the Air Pollution Control Association at Los Angeles, California, November 4-6, 1954.

The electrodes are graphite and the products of combustion are carbon dioxide and carbon monoxide. However, in the process of refining, great quantities of very finely divided silica and iron oxide are produced.

We are faced with the combination of high temperatures and large volumes of very finely divided particulate matter. Table I shows the size and distribution of the particles.

There are 3 methods of collecting the dust from the furnaces:

1. Hood over the furnace area.
2. Direct exhaustion through an outlet cut into the sidewall of the furnace.
3. Sheet metal hoods enclosing the furnace roof with intakes around the electrodes, over the charging door and tapping spout, and around the edge of the roof.

The difficulty with the first arrangement is the necessity of moving a tremendous air volume to collect the effluents. For this reason we rejected the idea, together with the fact that 3 overhead l ridge cranes pass over the furnaces, and we could not install the hoods under the crane ways.

The second system is adaptable to large furnaces (melting charges of 25 T. or more).

Direct roof hoods (third method) will not stand the eddy currents flowing around the electrodes on large furnaces—they burn up. However, hoods built directly on the furnaces work very well on smaller furnaces and have given us no trouble.

Ducts were run from the 4 furnaces to a common collection point and then the fun began.

All the foundries joined together and installed a wet collector at one of the other foundries. This collector was tested and passed by an Air Pollution Control officer.

We then purchased 2 of these collectors and installed them. We qualified the first one by the "skin of our teeth" and then installed the second one, upon which we were unable to get a clearance. Then we went back and retested the first one; it would not pass the test.

The difficulty with this type of collector was the impossibility of wetting the particulate matter. Experimenting with wetting agents, we blew soap bubbles all over Vernon—but each soap bubble was filled with smog. That was the end of wet collectors.

We then decided to investigate electrostatic precipitators and collected a large sample of dust and sent it to the manufacturer to test the collection possibilities. Much to everybody's amazement, the smoke went right through the collector and we were advised that we would have to introduce moisture into the system in order to get good results. We decided to have *no* part of any wet system.

The only method left was the bag-house method. We had a spare bag-house of fair size in the yard and got a permit to install it. This was done and the bag-house did a good job; we received an operating permit. Approximately 3 weeks later we burned up the bag-house. However, the experiment showed that some type of bag-house would work. Two things were apparent: first, we had to work out some kind of temperature control and second, the type of bags had a lot to do with the possibility of shaking clean, and the shaking mechanism would have to be more powerful.

We then installed a bag-house unit on an experimental basis which incorporated a blow-back feature. In other words, when the shaking mechanism operated the air flow was reversed, the idea being to blow the dust loose from the bags. These bags were made of wool and we soon discovered that it was impossible to free the dust, even though we used the blow-back while shaking.

It was then decided that a stronger shaking action was required and that the material used in the bags must be such that the dust cake would shake loose. We found a small tubular bag unit, installed it, found that the shaking mechanism was satisfactory and, after trying several types of bags, selected Orlon with no nap on either side.

Even though we had burned up one bag house, temperature did not seem to be an insurmountable problem. Temperatures in the bag house averaged 112° F., dry bulb, and 76° F., wet bulb, with peaks as high as 350° F. These high peaks were of short duration (not longer than ten minutes) and were caused by hot electrodes being raised out of the furnace just after tapping the heat. This placed the hot ends of the electrodes in the roof hood but circulating air drawn in around the roof edge cooled them rapidly.

Knowing that the dust would cake and pack easily, it became necessary to give careful consideration to the ratio of cloth area to air intake. Finally a ratio of not more than 2 ft.^{3} of air per ft.^{2} of cloth area was specified. The higher the ratio the harder the dust would cake on the bags, making it difficult to shake it off and requiring a longer shaking period. Air volumes were selected from experience gained when we were operating with the wet collectors and the data for each of the 4 furnaces is shown in Table II.

The manufacturer recommended 17,000 cfm. to exhaust the No. 1 furnace satisfactorily. However, this is a top-charge furnace and large openings had to be provided to accommodate the roof-raising mechanism. In addition we needed cooling air from some source and decided to take it in over the roof. This air flow also

TABLE II

Data for Calculation of Furnace Exhaust Volumes

Furnace	No. 1	No. 2	No. 3	No. 4
Capacity	6 T.	6 T.	1 T.	3 T.
Shell (diam.)	9 ft.	9 ft.	5 ft.	6 ft.
l ining (brick)	9 in.	12 in.	9 in.	9 in.
Practice	Basic	Acid	Basic	Acid
Charge	Top	Door	Door	Top
Exhaust duct	30 in.	24 in.	12 in.	16 in.

helped to keep the hood cool. We specified a 30 in. diameter duct capable of handling 20,850 cfm.

The total air volume necessary to properly exhaust the furnaces is 41,450 cfm. To this we added 8,550 cfm. as reserve cooling air and specified 50,000 cfm. In order to move this air volume we specified 2 fans, each having a capacity of 25,000 cfm. and driven by 50 hp. motors, and one stand-by fan with a capacity of 12,000 cfm. and driven by a 30 hp. motor.

Collector Design

With these basic points settled, the collector itself was designed. It is a 4-section bag house. Dust laden air enters a classifier section and is distributed into the 4 sections of the bag house. Each section may be closed off in case a repair job is necessary while the other 3 operate. Three sections have sufficient capacity to carry the full load.

The shaking mechanism located at the top of the bags is electrically controlled by a timer and each section of the bag house shakes 10 sec./hr. The shaking section is also under back-pressure which helps blow the dust off the bags. The 3 operating sections carry the load of incoming dust during the shaking period.

The total cloth area of all 4 sections is 26,174 ft.^{2} with a ratio of 1.91 cfm. to 1.0 ft.^{2} of cloth area. When only 3 sections are operating, the ratio is 2.54 cfm. to 1.0 ft.^{2} of cloth area. As noted before, Orlon tubular bags are used. This material will perform satisfactorily at temperatures up to 350° F.

Each duct from the furnaces was provided with a damper to balance the air flow so that each furnace could be properly exhausted. If one furnace should be shut down for any reason the damper may be closed. With 2 furnaces down and both dampers closed, 1 fan may also be shut down. Sliding gates are provided in front of the intake of each fan and can be closed in case of trouble or when 2 furnaces are down.

An outside air-intake damper is located in the classifier in a 48 in. x 48 in. frame with 6 in. wide damper sections. The damper shafts extend outside the frames and are connected to one operating arm. This outside air intake is operated by a modulating control set for 175° F. The higher the temperature rises the more the dampers open. Thermocouples are located in the center of the classifier section. If the temperature rises to 212° F. the intake dampers will open wide and the No. 3 fan (12,000 cfm.) which is electrically interlocked with the dampers, automatically starts and pulls in outside air until the temperature in the classifier section drops.

The same sort of closing damper is mounted on the exhaust of the No. 3 fan, and it opens when the fan starts. It is interlocked with the air intake damper and closes as soon as the fan stops, so no air can be taken in when the fan is off. The No. 3 fan serves mainly to keep temperature down in case of a hot flash, but it is also a standby in case of failure of one of the fans or motors.

When the collector was put into service, all dampers were left wide open and adjustment made so each furnace was exhausted properly. After a 24 hr. run, readings of temperature and air volume were taken in each duct, as follows: No. 1, 160° F. and 17,254 cfm.; No. 2, 108° F. and 10,934 cfm.; Nos. 3 and 4 (combined duct) 114° F. and 9,557 cfm. Average temperature, 127.3° F. and total air volume, 37,745 cfm.

Further adjustment was made so that oxygen could be blown into the furnaces. The dampers had to be opened a little more to take care of the heavy smoke created by the blowing. The temperature in the bag house would rise approximately 10° F. above the temperature it was running at the time, and no smoke was visible from exhaust stacks. The intakes had to be screened because the furnace operators would lose their hats in the intake of the furnace exhaust pipes. We screened them with 1 in. expanded metal so as not to close them up too much. Pitot tube readings were again taken in the ducts after screening and readjustment with the following results: No. 1, 19,759 cfm.; No. 2, 11,625 cfm.; Nos. 3 and 4, 8,147 cfm. Total air volume, 39,531 cfm. This permits about 10,000 cfm. of cooling air before reaching the capacity of the collector.

By running all furnaces into a common collector, one furnace helps to cool another. They are very seldom at the hot stage at the same time. By observation and temperature records taken of the collector, they very seldom need added air unless 2 furnaces should be tapped at the same time, when both of them have the hot electrodes in the hood out of the furnace. This makes for a hot spot when air circulates around the electrodes until they are cooled.

Maintenance

Maintenance on the dry collectors is very low. It consists of an inspection every week-end and takes from 1 to 1.5 hr. including lubrication. In particular, on the furnace collector a very short shaking cycle is used (10 sec. every hr. for each of the 4 sections) and this is sufficient to keep the bags clean; pressure across the bags runs up to 4 in., manometer gauge, and comes down to 2 in. after shaking. The dust hoppers are continuous from one end to the other (1 on each side over 2 sections) and are provided with a screw conveyor. Discharge is truck-high on the floor so the dust may be dumped directly into a truck.

Maintenance on furnace hoods and duct work has been nil for 1.5 years (since the system has been in operation).

The bags are still in very good condition. Some bags have been replaced but not because of deterioration by heat or acid. Orlon tubes for this collector cost, at present, $7.80 each. Cotton bags are cheaper by about $3.00 but would require a longer shaking cycle and, consequently, would wear out much faster.

Plant Cost

The purchase price of this bag house, including fans,

motors, starters and temperature control equipment, was $41,259.00; installation of control equipment cost $800.00; and plant installation, including foundation, wiring and plant labor cost $19,212.00. Total cost, $61,271.00.

According to our information from the manufacturer, a bag house this size would, at present, cost about $1.00/ft.^{3} of air required. A smaller operation, say a 1.5 or 2 ton furnace, would run into $1.50/ft.^{3} of air required for a 4-section continuous operation. The 4-section bag house has features not to be overlooked.

For single furnace operation, this cost could probably be reduced considerably if a 1-section bag house were used and the bags shaken at the time of charging the furnace by interlocking the bag-house fan motor with the main disconnect of the furnace power switch.

In our case, capital investment in smog-control equipment amounts to approximately 10% of our total capital investment. Prior to the Air Pollution Control Act, this figure was approximately 5% of capital investment.

Operating Cost

The cost of operating this equipment is approximately $2,601.15 per month, detailed as follows:

	Per Month Average
1 Dump truck load mud daily @ $7.00 1 Truck load dust daily @ $6.00	$ 286.00
Pump tank truck service (flat charge)	400.00
Operating labor (Schneible Unit)	264.00
Maintenance labor (estimate)	50.00
Repair labor (estimate)	50.00
Repair materials (estimate)	100.00
Depreciation ($183,000—15 year life)	1,000.00
Power— (198.5 hp. for 528 hr. at $0.006/kw.-hr.)	451.15
Total	$2,601.15

Conclusion

In conclusion, our experience shows that the important points in any bag-house installation are sufficient capacity, provision for automatically drawing in outside cooling air to control temperature, and fully automatic operation.

(Continued from page 9)

Smelting and Refining of Copper-Base Alloys

tion units and the necessary properly designed control units, it is then incumbent upon them to use these at maximum efficiency. Production personnel must combine the knowledge gained from the research department with their own practical experience and work toward the goal of optimum economic production. Greatest emphasis must be given to the control of losses during the smelting and refining operation in order to achieve the lowest possible production cost. This involves:

1. Proper selection and preparation of material to be charged,
2. Proper order of charging since, in many instances, high melting point scrap can be introduced into the molten bath and melted at a much lower temperature than would be necessary were it charged directly into the furnace and heated,
3. The correct use of the correct flux at the correct time, and
4. The exercise of proper procedure during the tapping operation.

In the experience of the authors, there is no serious trouble in operating a properly designed baghouse. The common complaint of "down time" is eliminated by allowing sufficient capacity in the design to permit efficient filtration, even when a cell must be cut out of the system during repairs or bag replacement.

The control equipment was purchased and erected at a total cost of approximately $125,000.00. As opposed to an original investment of from $2.00 to $2.50/cfm., the advantages of a dust-collector system in the secondary smelter are many. In the first place, the recovered product is marketable at a figure relatively proportional to the current price and availability of zinc. Secondly, the use of a dust-collection exhaust system is something which has been sought by all ingot-production experts. It stabilizes furnace operation by controlling draft fluctuation. Finally, plant and atmosphere cleanliness are assured. At this plant we have collected more than 1,000,000 lb. of flue dust in the first 2 years of smelter operation.

Acknowledgement

The authors gratefully acknowledge the co-operation and assistance of Earl S. Schwartz, Vice President, H. Kramer and Co., and Staff.

(Continued from page 12)

Engineering Waste Disposal

Unresolved problems are: (1) the cost of reducing the rubbish in size before discharge to the sewer so that it will not foul sewage pumps, (2) the effective separation of the small amounts of dense materials that would tend to settle in the sewer, and (3) the effect of an increase of about 700% in the quantities of organic material removed at the sewage-treatment plant for digestion and disposal.

If a hypothetical scheme such as this can prove economically competitive with incineration, it most certainly would prove to be less objectionable to air-pollution-control authorities. In the pursuance of such alternative disposal methods may lie the answer to our present dilemma in relating waste disposal to air-pollution control.

Some Factors Affecting Fly-ash Collector Performance On Large Pulverized Fuel-fired Boilers*

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For many years, the collection of fly ash from pulverized-fuel-fired boilers was a relatively simple problem from the collector manufacturers' point of view; efficiency demands were not great, with 80 to 90% efficiency meeting most collection requirements. The characteristics of the ash encountered on the large majority of units were such that either high-efficiency cyclonic collectors or electrostatic precipitators could satisfactorily meet the requirements. Pulverized-fuel fly ash ordinarily was of such a character that precipitators of ½ to ¼ the size regularly used in cement and metallurgical operations for equivalent gas volumes and efficiencies were successful. At the present time, with the new demand for very high efficiencies, low stack emissions, and numerous changes in steam-generating unit design, the picture is apparently changing. It has become necessary to regard the collection equipment as a necessary auxiliary of the furnace and to obtain peak performance at all times. This is occurring at the same time that design requirements for the station appear to be working against the collector. This paper endeavors to bring out some of the major factors in operation and design which must be considered in any over-all evaluation of the collection problem, and to raise an appreciation of their importance in the minds of the responsible persons. Some of these factors pertain to high-efficiency cyclonic collectors, others pertain to Cottrell electrical precipitators, and most are common to both. It will be apparent from the text into which category each factor falls.

Electrical Characteristics of Fly Ash

A number of papers have been presented at engineering society meetings regarding the effect of the apparent electrical resistivity of the collected fly ash on the performance of an electrical precipitator.[1-2-3-4] We will only reiterate that high ash resistivity can of itself result in reduced precipitator efficiency to the extent of ½ or even ¼ of the original design efficiency.

White[5] has discussed the effect of SO_3 on apparent resistivity of fly ash and has illustrated how this resistivity decreased as the SO_3 content of the ash increased. Johnstone [6], Harlow[7], and Widell[8] have shown that SO_3 content of flue gases can be strongly influenced by steam-generator design. The temperature and rate of combustion, the contact time with catalytic metal surfaces, and the temperatures at time of contact with the metal surfaces all appear to have a bearing on the problem.

The current design trend appears to be to adjust all of these conditions so as to minimize corrosion difficulties in the boiler elements and air heaters. It is now beginning to appear to us that the trend has reached a point where electrical resistivity of the ash is being adversely affected, where proper precipitator performance may not be achieved within the design parameters currently in use. This problem then becomes a matter of close evaluation of net savings from lower temperature operation without corrosion, acceptance of some corrosion, or purchase of larger and/or more complex precipitators for the same job.

High carbon content (over about 20% by weight) in the ash also has been shown to have an adverse effect on precipitator-collection performance.[9] This is largely attributed to the phenomenon in which carbon particles striking a grounded collecting plate lose their charge rapidly and completely and are then attracted to the discharge electrodes, recharged, reprecipitated, and so on until the gas flow through the collector carries them out of the unit. A larger, lower-velocity precipitator may tend to decrease the trouble, but does not attack the problem directly.

The high-efficiency cyclonic collector combined with a Cottrell precipitator can alleviate these problems in some instances (Fig. 1). The physical fact that very high

(1) Schmidt, W. A., "Electrostatic Precipitation and Mechanical Dust Collection," *Ind. Eng. Chem., 41,* 2428 (1949).

(2) Schmidt, W. A., Sproull, W. T., and Nakada, Yoshinao, "How the Operation of a Cottrell Precipitator Is Affected by the Resistivity of the Collected Material," Presented at the 170th General Meeting of the Am. Inst. Mech. Engrs., New York N.Y., February 15, 1950.

(3) Sproull, W. T., and Nakada, Yoshinao, "Operation of Cottrell Precipitators—Effects of Moisture and Temperature," *Ind. Eng. Chem., 43,* 1350 (1951).

(4) Heinrich, D. O., "The Science and Art of Electro-Precipitation," *Eng. and Boiler House Rev. (England),* June 1953.

*Presented at the Annual Meeting of the American Society of Mechanical Engineers at New York, N. Y., November 28 to December 3, 1954.

(5) White, H. J., "The Role of Corona Discharge in the Electrical Precipitation Process," *Elec. Eng., 71,* 67 (1952).

(6) Johnstone, H. F., "An Electrical Method for the Determination of the Dew Point of Flue Gases," Univ. of Ill. Eng. Exp. Station, *Circular 20.*

(7) Harlow, W. F., "Causes of High Dew Point Temperatures in Boiler Flue Gases," *Proc. Inst. Mech. Engrs. (England), 151,* 293, (1944).

(8) Widell, Torsten, "Formation of Sulfur Trioxide in Flue Gas," *Combustion,* 53 (June 1953).

(9) Bauman, H. A., "Air Pollution Prevention in Electric Generating Stations," *Elec. Eng., 72,* 200 (1953).

TABLE I
Apparent Electrical Resistivity of Fly Ash

Collector	Plant A[1] ohm-cm.[a]	Plant B ohm-cm.	Plant C ohm-cm.	Plant D ohm-cm.
Multiclone catch	3.2×10^{10}	8.2×10^{10}	6.6×10^{11}	4.0×10^{11}
Precipitator catch	7.0×10^{9}	5.8×10^{8}	5.4×10^{10}	2.8×10^{9}

(a) Laboratory resistivities determined at 300° with 5% water vapor by volume in the gas stream.

carbon ashes (over 20%) generally carry a higher percentage of carbon in the coarser fractions of the ash combines with the higher efficiency of cyclonic collectors on the coarse fractions of the ash to give an exit ash lower in carbon content. Thus, the installation of such collectors ahead of the electrical precipitator has resulted in considerable improvement in precipitator performance on some installations plagued by this problem, since the precipitator voltage and current could be raised considerably above the old electrical control points after the highly conductive carbon particles were removed.

We also have found in an investigation of combination high-efficiency Multicyclone collectors and Cottrell precipitators that the resistivity of the ash caught by the Multiclone was higher than that caught by the precipitators (Table I). It is our theory that this is largely due to the greater surface for gas (SO_3) adsorption, the consequently larger leakage path for the accumulated charge, and the more homogeneous nature of the precipitated layer.

In addition to the foregoing, the combination unit has an intangible advantage on new boiler installations of unpredictable nature as to ash characteristics; that is, the mechanical collector will supply a rather dependable base collection of the ash with the result that, if precipitator performance is impaired by variable electrical characteristics of the ash, the stack loss is held to a minimum while corrective measures are being sought or applied.

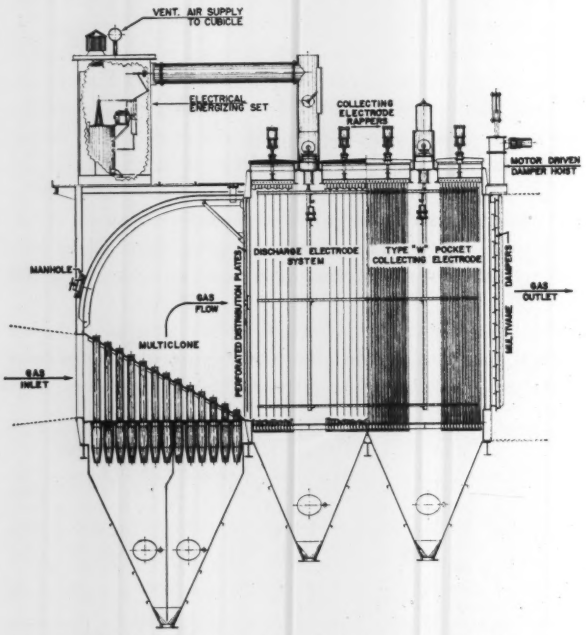

Fig. 1. Cross-Sectional Assembly of an Integral CMP.

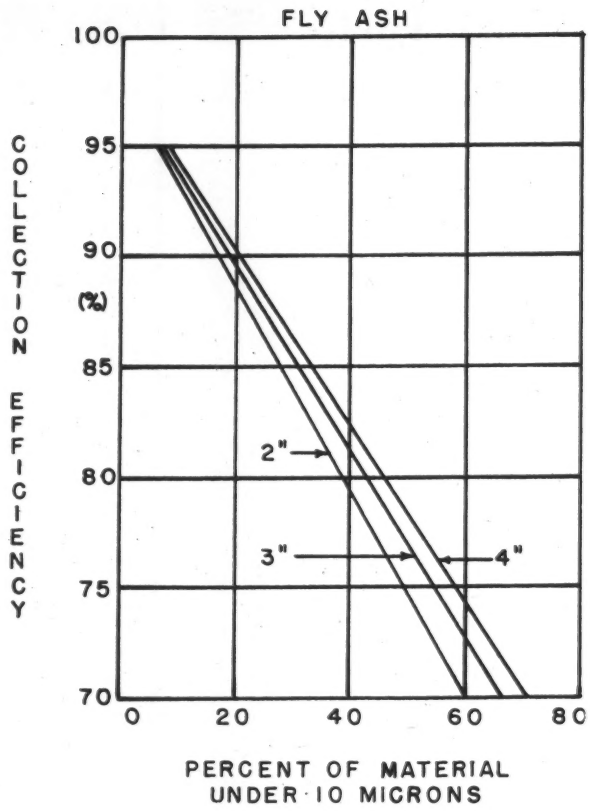

Fig. 2. Multiclone Collection Efficiency.

Particle Size

The importance of the particle-size distribution of fly ash to high-efficiency cyclonic-collector performance is well known and has been discussed in technical papers and commercial bulletins.[10,11] For the purpose of illustrating some problems involved in their selection and operation, we need only note that the inertial forces used in ash separation in these collectors depend on size, shape, and density of the particles, as well as other factors; that these collectors generally perform very efficiently on particles over a nominal 10 μ in diameter; and that they usually have a break in efficiency for particles somewhere in the range of 5 to 10 μ in size. To evaluate performance of the collector, it then becomes necessary to know its characteristics with reference to particle size and to know or be able to reasonably predict the particle-size distribution.

The collector manufacturers have met the first prob-

(10) O'Mara, R. F., and Rich, P. G., "Mechanical Collector Efficiency Curves—Method of Construction and Use." Presented at Fly Ash Symposium of ASME in New York, N.Y., November 27, 1944.

(11) O'Mara, R. F., "Current Trends in Fly Ash Recovery," *Combustion, 21,* 38 (April 1950).

TABLE II
Particle Size of Fly Ash From Boiler Outlet

Plant	Per Cent 0 - 10 μ
1	35 - 38
2	27 - 36
3	31
4	36.8 - 51.9
5	33.3
6	34 - 39
7	54 - 58
8	28 - 40
9	45 - 47
10	49
11	49 - 51
12	33 - 35
13	42.5
14	47.3 - 48.7
15	32.6 - 38.2
16	21.6 - 26.6
17	34.3 - 49.1
18	21.4 - 32.3
19	33.9 - 40.0
20	21.3
21	26.1

m by publishing data on performance as a function of particle size and pressure drop across the collector. A typical example is shown in Fig. 2, which is a curve for one type of Western Precipitation Corporation's Multiclone collector. It can be noted that efficiencies expected at 2.5 in. VWG pressure drop across the collector would vary from about 87.2-82.2% to 78.5% for ashes with a total of 25, 35, and 45% minus 10 μ material, respectively.

The second problem (knowing or predicting the particle size of the ash) can be determined from plant experience (typical data for a variety of pulverized-fuel plants are shown in Table II) or by obtaining a sample and subjecting it to laboratory analysis. At the present time, there is no completely satisfactory or universally accepted method for this analysis. Our preference is for a liquid sedimentation-decantation method developed in Western Precipitation Corporation's laboratory[12] or for the Roller air-elutriation method.[13] These methods develop a fractional partize-size distribution based on settling rates and reported as the size of theoretical spheres of equal density and equal settling rate. For the operator or designer, it then becomes necessary not only to know or specify the particle-size distribution, but also the method by which it is obtained.

As far as the Cottrell electrical precipitator is concerned, there is no theoretical limitation on the particle size to be collected. Practically, there are problems with the very large or very small particles. On the coarse side, the ash ordinarily runs high in carbon and losses are experienced from erosion as the particle bounces through the collector as already discussed. On the very fine side, a homogeneous layer of ash can readily pack and form a dense layer, which makes the problem of rapping or removing the collected dust from the collecting surfaces and discharge members more difficult.

Typical data on particle-size distributions through a collector system are shown in Table III to illustrate the type of variation to be expected not only from boiler to boiler but on the same boiler at different times. It may be seen that the catch from the mechanical-collector hoppers ran from 30.3 to 37.4% minus 10 μ material with the remainder in the coarser fractions, while the catch of the Cottrell precipitator hoppers was from 84.5 to 97.4% minus 10 μ in size. Data on Plant D are for the same boiler at different loads and for Plant E are for one boiler on different days with substantially the same steaming rate. Both of these boilers are of similar rating and burn approximately the same semi-bituminous, deep-mined coal. All of the factors in combustion appear to enter in the end result and make exact prediction very difficult; that is, (a) coal analysis, (b) fineness of grind,

(12) Western Precipitation Corporation, "Particle Size," a bulletin.

(13) Roller, P. S., "Separation and Size Distribution of Microscopic Particles—An Air Analyzer for Fine Powders," *Bur. Mines Tech. Paper 490* (1931).

TABLE III
Particle Size of Collected Fly Ash in Combination of High-Efficency Cyclonic Collector and Cottrell Electrical Precipitator (Per Cent)

Source	Particle Size[a] Distribution Fraction	September 22, 1953				September 26, 1953			
		% at Inlet	% at Cyclone Hopper	% at 1st Precip. Hopper	% at 2nd Precip. Hopper	% at Inlet	% at Cyclone Hopper	% at 1st Precip. Hopper	% at 2nd Precip. Hopper
Plant D	0 — 10 μ	38.3	36.4	93.5	97.4	40.0	30.3	95.7	95.5
	10 — 20 μ	17.8	17.8	3.8	1.3	18.7	22.8	3.7	2.4
	20 — 44 μ	25.1	27.2	1.1	0.2	23.2	26.6	0.3	0.1
	+ 44 μ	18.8	18.6	1.6	1.1	18.1	20.3	0.3	2.0
		July 13, 1953				July 14, 1953			
Plant E	0 — 10 μ	48.7	37.0	89.9	84.5	47.3	37.4	93.3	94.6
	10 — 20 μ	22.1	23.3	3.9	2.7	18.6	21.2	2.6	2.2
	20 — 44 μ	18.3	20.1	2.2	2.5	19.0	25.2	1.5	1.3
	+ 44 μ	10.9	19.6	4.0	10.3	15.1	16.2	2.6	1.9

(a) All of the above particle-size determinations were made by the liquid sedimentation-decantation method.

(c) percentage of ash slagged down in furnace and (d) rate of combustion and percentage of excess air can all cause changes in these figures.

Dust Loading

The next problems we would like to discuss are those associated with the quantity of dust to be handled by the collector. For many years, it has been common to use a figure of about 85% of the ash in the coal as fired to predict the amount of ash coming to the collector in the case of dry-bottom furnaces. This has calculated to a loading of from 2 to 4 gr./ft.^{3} at collector-inlet conditions for many United States coals. While this still appears to be fairly true, we are finding some of the newer, more efficient furnaces slagging a much higher percentage of the total ash and reducing the collector load to a very considerable degree. The extreme case to-date has been one where only 25% of the ash in the coal as fired reaches the collector, with several others ranging around 50%.

At very low loadings, say about 0.8 gr./ft.^{3}, we find that cyclonic collectors tend to show decreased efficiency, even though particle size and pressure drop do not change. Cottrell precipitators, at very low dust loads, also show an efficiency decrease. We ascribe these losses largely to the mechanical features of the designs in which very small quantities of dust are being caught in very large devices, and the statistical effect of losing a given particle by bouncing, sneak-by, or erosion becomes much greater.

As a typical example, let us consider a 100,000-cfm. unit collector with a single cyclonic-collector section, followed by 2 sections of electrostatic precipitator. Such a unit might easily have 3 hoppers in series, 1 under the cyclonic collector and 1 under each electrical section. For an over-all collection of 96.8%, we can assume a collection of 80% in the cyclonic hopper, 60% of the remainder in the first electrical section, and 60% in the second electrical section. This reduces to an 80 + 12 +4.8 or 96.8% collection of the original ash. On an assumed 2 gr./ft.^{3} inlet, the catches would then be

Cyclone hopper	1371 lb./hr.
1st electrical section	206 lb./hr.
2nd electrical section	82 lb./hr.

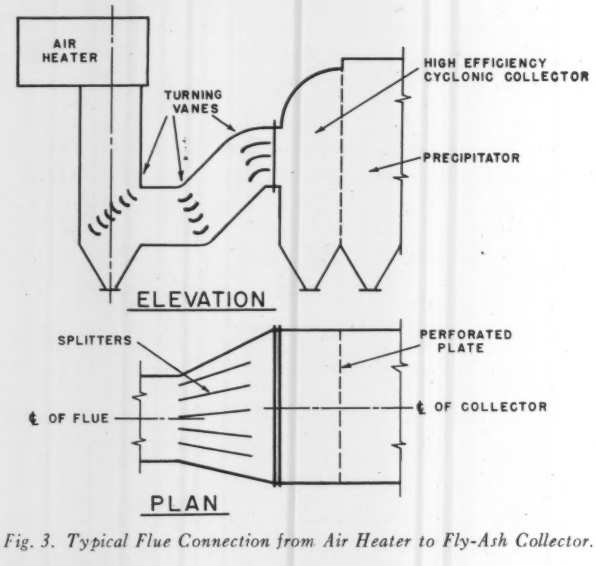

Fig. 3. Typical Flue Connection from Air Heater to Fly-Ash Collector.

The problems associated with this distribution also vary. The first hopper has a mass problem in which the dust can deaerate and bridge on long standing, and the last hopper with a small amount of very fine material can re-entrain and blow away if the slightest valve leak exists. We are of the opinion that the closest approach to a solution of this phase of the problem is to withdraw ash from the collector as rapidly as possible, with continuous withdrawal as an ideal. In any case, meticulous maintenance of the ash-handling system, and particularly of the timing mechanism and valves, is a necessity, if very high collector efficiencies are to be maintained.

In view of the foregoing, the collector manufacturer must protect himself against cases involving low dust loading by means of a specified minimum inlet or a specified outlet option on a predicted inlet, in combination with the percentage efficiency for which the unit was designed. This is a reasonable approach to avoiding difficulty between customer and manufacturer when the above factors are carefully evaluated.

Gas and Dust Distribution

In common with the other factors so far considered, gas and dust distribution figure heavily in obtaining peak collector performance. In practically all cases, the available ground area for collector installation is very limited. This results in a strong tendency to make very short flue connections between air heaters and collector inlets. In other cases, the fact that the unit was originally designed without collector equipment, or with equipment which no longer meets requirements, complicates the picture. The net effect is to give physical arrangements that result in very badly distorted and offset flue connections.

A fairly typical arrangement of air heater and collector is shown in Fig. 3. In this case, without turning vanes under the air heater, the tendency is for the gas and fly ash to be predominantly in the bottom half of the horizontal run of the flue entering the collector. This could result in both low efficiency in the collector or a bad wear problem on the parts of the collector exposed to the high dust concentration. In addition to the problem of bends, the designer is ordinarily faced with the necessity of flue expansion, as normal collector-inlet velocities are usually below those common for flue velocities. These expansions are ordinarily made at a much greater angle than a venturi discharge angle which the gas could be expected to follow. This requires the use of splitters to guide both gas and dust until the collector is reached.

The use of splitters and vanes is predicated on having a reasonably uniform profile of velocity and dust distribution at one point and then trying to preserve this same relative profile by guiding the streams. On the

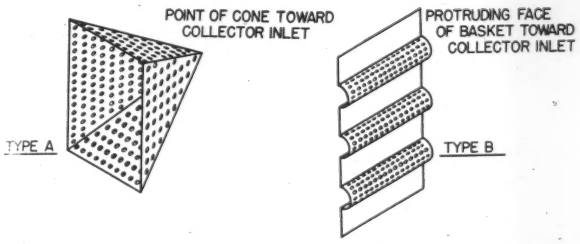

Fig. 4. Perforated Plate Gas Distribution Baskets (Type A—Point Cone toward Collector Inlet; Type B—Protruding Face of basket ward Collector Inlet).

her hand, it has been shown[14] that the correction of ese profiles required the expenditure of energy, ordin-ily as pressure drop, across a special distribution facility. hus, it is customary on Cottrell precipitator inlets to use perforated distribution plate with from 35% to 40% en area for final correction of the stream. For very bad stribution problems, more drastic measures are required. g. 4 shows some of these that have been used success-lly. The first is a perforated plate pyramid used to in distribution in a flue expanding in all directions; e next is a perforated plate—half cylinder arrangement nerally used to aid distribution in a single plane; series arrangements of up to 4 perforated plates also have been sed. With these facilities, hole blinding problems may oc-ur and rapping devices are often necessary. The problems associated with the device must be accepted, as good distribution is an absolute necessity for peak performance.

Much can be accomplished by the designer using logical study and judgment in the flue layout. Recently, there is a trend to aid this judgment by the use of model studies, generally in water models or in wind-tunnel studies. These can be of great help in the more complicated problems and their use is certainly one of the first considerations to be evaluated by the flue designer.

Temperature and Mixed Firing

There are several ways in which temperature can affect the operation of fly-ash collectors: (a) the effect on apparent electrical resistivity of the fly ash, (b) corrosion problems, and (c) mechanical problems, such as plugging of collectors.

The temperature effect on electrical resistivity of the ash has been well covered in other papers and will not be discussed here.[3]

Corrosion problems in collectors arise mainly from the present trend to low temperatures at the air-heater outlets, the temperature at this point usually being chosen for the lowest point which will not seriously corrode the heater. This makes it imperative that heat insulation be made as complete as possible, and air inleakage kept to a minimum, or all external surfaces of the collector may be expected to corrode owing to metal temperatures below dew point. This is aggravated by the general practice of installing collectors exposed to the weather, outside of the main structure. Particular difficulty is usually noted in stagnant areas within the collector, such as the hoppers, where extended periods of ash storage allow surfaces to become cold in spite of good insulation. Light wind- and rain-proof structures over the tops and around hoppers can be a considerable aid in improving this situation.

Many new installations are being designed to burn coal, oil, or natural gas, either separately or in combination. Other, older boilers, have been modified to burn the same fuels. In these cases, it is common for the air-heater exit temperature to drop to 250° F. or less, when burning oil or gas, if the original design was for about 275° F. on coal-firing. Frequently this is enough of a drop to cause trouble from soot, tar, and water mixtures being collected in the case of oil-firing, and to cause trouble from condensed water with a considerable acid content in the case of gas-firing. Such materials deposited in the collector hoppers have a strong tendency to corrode and/or foul the ash-handling system.

Several installations have satisfactorily used mixed-firing of oil and coal with up to 50 or 60% of the fuel being oil, both fuels being distributed across the furnace. The usual recommendation on straight oil-firing has been to cut off the power on electrical precipitators, partly due to the explosion hazard and partly due to the desire to avoid complete fouling of the ash-handling system. However, there are a number of straight oil-fired units

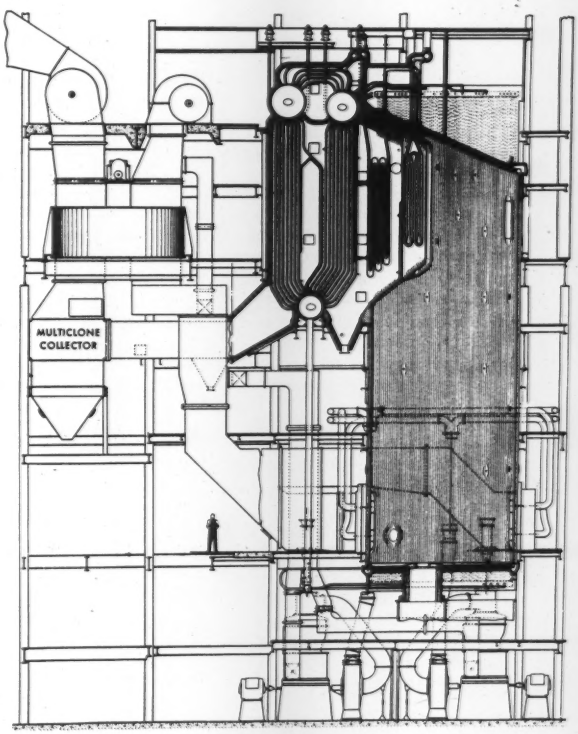

Fig. 5. Multiclone Ahead of Air Heater.

(3) See footnote 3, p. 27.
(14) Stoker, R. L., "Methods of Producing Uniform Velocity Distribution," *Ind. Eng. Chem., 38,* 623 (1946).

using mechanical collectors for the reduction of stack emissions during soot-blowing periods where facilities are provided for proper disposal of the collected material. At the present time, there are a few installations in which provisions have been made to by-pass the collectors during extended periods of oil- or gas-firing, and this is a point which should be considered seriously by designers planning on such extended runs on fuels other than coal. This entails a greater first cost of installation, but may represent a very substantial saving in future maintenance and rebuilding work on large collectors.

At the high end of the temperature scale, occasional difficulty has been found where mechanical collectors are installed ahead of the air heaters, and the fly ash exhibited a tendency to stick or agglomerate (Fig. 5). This difficulty has been met by mechanical means such as air lances or rappers mounted in or on the collector elements to keep the material flowing. We have not found it practical to predict the exact conditions under which this trouble can occur and it must be dealt with as occasion demands. On some installations, other than steam-generating units, it has been possible to solve this problem by altering the temperature by 50 to 100° F., a solution not ordinarily possible in the case of large steam-generating units.

Equipment

The preceding discussion and other factors raise many questions which have no absolute answer and make it necessary for the operator to evaluate his collectors in the light of individual plant characteristics. As an aid in this evaluation, we have prepared the following check lists:

1. General

(a) Type and analysis of coal as it relates to the resultant ash characteristics, sulfur content in gases, moisture of combustion, and abrasiveness of ash.
(b) Characteristics of unit with regard to ash: quantity, particle size, electrical resistivity, carbon content.
(c) General layout: space available for collectors, possible flue arrangements, by-pass requirements for changes in fuel.
(d) Standards of performance required: past, present, and future ordinances and psychological factors.
(e) Ash handling system: Time cycle, proper sealing of hoppers, reliability, capacity.
(f) Operational methods: Start-up procedure to avoid difficulties during critical periods, maintenance requirements and schedules.

2. High-Efficiency Cyclonic Collectors

(a) Applicability to the collection problem.
(b) Efficiency versus particle size.
(c) Efficiency versus pressure drop.
(d) Tube design, size, and arrangement of dust inlets and throats as they relate to the properties of the fly ash.
(e) Provisions for variable-load operation, sectionalization of collectors.
(f) Arrangement and design from an accessibility and maintenance standpoint.
(g) Materials of construction, weights or gages of metal.
(h) Hopper storage, if any, related to fly-ash handling system; hopper-outlet size.
(i) Overload characteristics, gas and ash.
(j) Heat insulation, weatherproofing.

3. Cottrell Electrical Precipitators

(a) Applicability to the collection problem. Use alone or in conjunction with cyclonic collector. Leaving of space requirement for precipitator, with cyclonic unit only to be installed at present.
(b) Collecting-electrode surface area, type and design of collecting electrodes.
(c) Discharge-electrode size and type.
(d) Throughput velocity.
(e) Time of treatment in electrostatic field.
(f) Electrical sectionalization of unit.
(g) Rectifiers: Number, capacity, type—mechanical, electron tube, or selenium. (Include relative costs, initial and maintenance).
(h) Rapping: Type, control, cycle.
(i) Automatic controls: Purpose, design.
(j) Arrangement of parts and design for accessibility and maintenance.
(k) Materials of construction, weights or gages of metal.
(l) Hoppers: Baffling, capacity, ash-removal accessories, size of outlet.
(m) Overload characteristics of collector.
(n) Heat insulation, weatherproofing.

Summary

This paper has taken a broad view of the term "performance" of fly-ash collectors as referring not only to total solids collection or efficiency, but also to operation and maintenance aspects of performance. The relation of plant and boiler design to operation of collectors has also been considered. To summarize, the following aspects of collector performance were covered.

1. SO_3 is an effective conditioning agent to improve Cottrell electrical precipitator performance. The recent trend toward designing boilers for minimum contact of gases with interior surfaces may reduce the tendency of oxidation of SO_2 to SO_3 with adverse effects on precipitator performance.

2. Combination high-efficiency cyclonic collectors and Cottrell precipitators have both tangible and intangible advantages in the fine cleaning of pulverized-fuel-fired boiler gases.

3. The particle size of the fly ash from many boilers is about 35% minus 10 μ, which supports the applicability of high-efficiency cyclonic collectors.

4. The importance of good gas and dust distribution by the use of turning vanes, splitters, and perforated plate distribution facilities in the flues ahead of collectors cannot be overemphasized.

5. The trend toward low air-heater exit temperatures of 275° F. (or less) as opposed to the older practice of about 350° F. aggravates the condensation and corrosion, and the operating and maintenance problems in collectors.

6. The design of the boiler plant, as well as the design of the collectors themselves, has a very direct bearing on collector performance. A check list of collector-design features for evaluation purposes is given.

Adsorption of Binary Hydrocarbon Mixtures on Activated Charcoal — Molecular Weight Variation*

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The increasing number of industrial applications of charcoal-based separation systems, especially in the petroleum industry, have given a new interest to the study of the unit operation of adsorption.

The uptake of gases by charcoal has been known for almost 2 centuries, and during this time important research of this phenomenon has been accomplished; nevertheless, the data so far published fall short of those required for the multiple component systems in which adsorption is involved. Besides, limitations are placed on the usefulness of these data for the design of commercial charcoal-based separation systems because, in large part, they have been obtained under conditions not practical from a commercial standpoint.

Although most of the technical applications or processes involve gas mixtures rather than pure gases, published data deal mostly with simple adsorption, and those available for mixed adsorption have been recorded almost exclusively in dynamic systems.

Gas purification, recovery of solvents, separation of olefins from cracked gases, recovery of liquefied petroleum gases from natural refinery streams, are a few examples of the application of mixed adsorption. Some of these separations with a charcoal-based system have the advantage that low temperatures and high pressures are not required as they would be if a fractional distillation process were used.

It is customary to consider 3 types of mixed adsorption:

1. Single adsorbent and a mixture of gases.
2. One adsorbate and a mixture of adsorbents.
3. A mixed adsorbent and a mixture of gases.

The first type of mixed adsorption is by far the one of the greatest practical interest, and obtaining data on this type of adsorption was the goal of this research. A study of the molecular weight of the adsorbate, and the factors that influence it, has been made for a static system when binary mixtures of the gases ethane, propane, butane, and ethylene are adsorbed on charcoal.

Apparatus

A detailed diagram of the apparatus is shown in Fig 1. It consisted of an adsorption bulb (A) connected to a closed-end manometer (B) and to a gas burette (C), all 3 inside an air-thermostat case. Outside of the thermostat the system included a Cenco Hyvac vacuum pump powered by an Emerson electric motor, a modified McLeod gage, and gas manifold lines.

The heating system of the air-thermostat case included a 500-w. heating element that could be regulated by a variac, a 50-w. heating element used in conjunction with a Cenco-De Khotinsky bimetallic regulator, and a water-cooling coil of copper tubing. All 3 elements were installed in front of a 4-blade 6-in fan, rotating at 1,000 rpm. The temperature could be controlled within a range of 0.1° C. by adjusting the variac to a position depending on the room temperature, and by keeping a constant flow of cooling water.

The adsorption bulb housed a copper-beryllium alloy

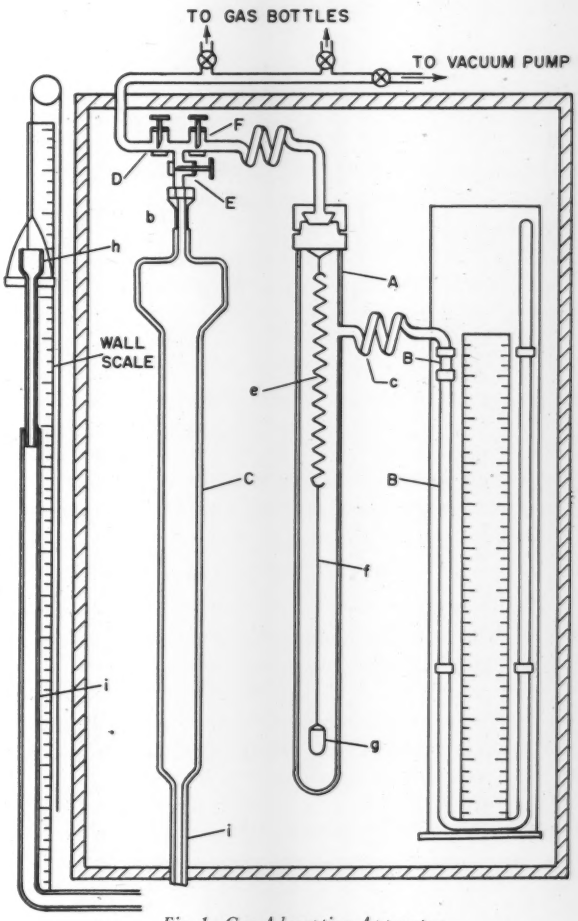

Fig. 1. Gas Adsorption Apparatus.

*Reprinted from *The Trend in Engineering at the University of Washington*, January, 1955.

spring or sorption balance (e) suspended from the top of the adsorption bulb on a small wire clip fitting in milled grooves on either side of the top brass fitting. Its lower end was connected through a silica fiber (f) to an aluminum bucket (g) which contained the adsorbent. Columbia activated charcoal, grade SX, in pellets of 6 to 8 mesh, was used as the adsorbent in this case. Pin-point holes were made in the aluminum bucket to allow the gas to pass through.

The closed-end manometer was made up of 10-mm. pyrex tubing with the closed end 86 cm. long. The gas burette consisted of 15 x 20-mm. pyrex tubing 67 cm. in length, with a 5-cm. bulb close to the upper end. The lower end of the gas burette was connected to a leveling bulb (h) by a ¼-in. tygon tubing, forming the leveling line (i). The leveling bulb was suspended from the ceiling by a pulley alongside of an exactly calibrated meter scale. This leveling line controlled the pressure and volume in the gas burette.

The manifold consisted of 3/16-in. copper tubing, 3-¼-in. Hoke stainless-steel needle valves (D, E, F), and silver-soldered joints.

Additional parts of the equipment were a manifold tapper installed behind the closed-end manometer to eliminate the lag in the readings, an outgas furnace to outgas the charcoal, an electromagnet, which facilitated reading by reducing the spring oscillations, and a stationary cathetometer to measure the spring elongation.

The spring was calibrated by determining with the cathetometer the spring elongation caused by fractional analytical weights deposited in the aluminum bucket, while keeping the thermostat at a constant temperature of 25° C. The volume of the gas burette was determined from the weight of mercury to fill it. To determine the volume of the adsorption bulb, a certain amount of helium was introduced into the gas burette, and the temperature and pressure were recorded. Then the same helium was allowed to occupy the adsorption bulb and the gas burette, and the pressure and temperature were recorded again. From the known volume of the gas burette, and by applying simultaneous solutions of 2 van der Waals equations for the 2 sets of readings recorded, the volume of the adsorption bulb was determined.

Experimental Procedure

The major steps involved in making a binary run consisted of mixing the gases, outgassing the charcoal, and obtaining data for the rate of adsorption and equilibrium.

After exhaustion of the gas burette and manifold with the vacuum pump, one of the gases was put into the gas burette to a pressure which was roughly estimated to give the desired amount of this gas. After the gas was allowed to remain at a constant temperature of 25° C. for some hours, a pressure reading was taken by positioning the mercury level in the burette at a reference dot and reading on the wall scale the mercury level in the leveling line. Following another exhaustion of the manifold the second gas was allowed into the gas burette until a pressure which was previously estimated to give the desired composition was approached. Mixing was facilitated by raising and lowering the leveling line several times; then the mixture was allowed to remain for several hr. at a constant temperature before reading the total pressure.

The charcoal already in the aluminum bucket was outgassed by using an outgas furnace, which raised the temperature up to 350° C., while vacuum was being pulled continuously on the adsorption bulb.

After the outgassing of the charcoal, the system was thermostated at 25° C. for several hr. At the end of this period the pressure in the gas burette was checked again, the top and bottom of the spring were recorded by means of the cathetometer, the manifold lines and adsorption bulb were completely evacuated, and all valves were closed. Just prior to time zero, valve F was opened. At time zero the adsorption bulb valve (E) was opened, allowing the gas into the adsorption bulb, while the oscillation dampener was turned on. The desired amount of gas allowed in the adsorption bulb was approximately estimated by a pressure reading of the closed-end manometer.

Simultaneous readings of the spring elongation with the cathetometer, and pressure readings of the closed-end manometer, were recorded at different times at the nearest second by reference to a stop clock. The runs were continued overnight for periods of 15 to 20 hr. until constant readings showed that equilibrium had been reached.

The pressure of the remaining gas in the burette and tubing between valves D, E, and F was determined by positioning the leveling line with the mercury at the reference dot in the gas burette and then reading the wall scale.

Four binary mixtures were made by different combinations of the gases used. For each binary mixture 6 runs were made; 3 runs were carried on at a pressure of approximately 0.7 to 0.8 atmospheres for mixtures in which the heavier component was in the proportion of 0.25, 0.50, and 0.75 mole fraction. The other 3 runs with the same mixtures were done at a pressure of 0.3 to 0.4 atmospheres.

Calculations

Calculations were made for each instant at which readings were taken.

To determine the volume occupied by a pure gas mole, the van de Waals equation was used:

$$[P + (a/V^2)]\ [V - b] = RT, \qquad (1)$$

where

P = absolute pressure,
a, b = van der Waals constants for pure gases,
V = volume of pure gas per mole,
R = gas constant,
T = absolute temperature.

Solving for V yields

$$V = \frac{RT}{P+(a/V^2)} + b. \qquad (2)$$

For calculation involving mixtures ( )$_m$, the van der Waals equation, with its constants properly corrected, was used:

$$V_m = \frac{RT}{P+(a_m/V^2)} + b_m, \qquad (3)$$

where

$$a_m^{1/2} = x_1 a_1^{1/2} + x_2 a_2^{1/2}, \qquad (4)$$

$$b_m = x_1 b_1 + x_2 b_2, \qquad (5)$$

and

x_1 being the mole fraction of a particular component.

The 3 main steps in the calculations were as follows:

1. Calculation of the Number of Moles of Gas Adsorbed

a) The number of moles of the first gas introduced into the gas burette was calculated from the known volume of the gas burette and V. The value of V was calculated by trial and error, using Eq. (2) in conjunction with the pressure and temperature readings. (The temperature was constant at 25° C. throughout.)

b) The total number of moles of mixture was calculated from the known volume of the gas burette and the value of V_m, which had been previously calculated by using Eq. (3) and the pressure and temperature readings. It was necessary first to assume a total number of moles of mixture, then to determine the corresponding gas composition for such an assumed value, and calculate the constants a_m and b_m with Eq. (4) and (5) to be used in Eq. (3). The volume of the total number of moles of mixture was then calculated and compared with the value first assumed. This procedure was repeated until the assumed and calculated values were the same.

c) The number of moles of gas remaining in the burette was determined by calculating V_m with Eq. (3), using the corresponding temperature and pressure readings. From the known volume occupied by the gas and V_m, the number of moles was calculated.

d) The number of moles of gas transferred to the adsorption bulb was calculated by subtracting the number of moles remaining in the burette from the original number of moles of gas.

e) The number of unadsorbed moles of gas remaining in the adsorption bulb was calculated from the known volume of the adsorption bulb and the corresponding pressure and temperature. Equation (3) was used in these calculations, with its constants continuously corrected for the variation in mixture composition due to the different adsorption capacity of the charcoal for each component.

f) The number of moles of gas adsorbed was determined by subtracting the unadsorbed moles from the total number of moles transferred into the adsorption bulb.

2. Determination of the Weight of the Adsorbate

The weight of gas adsorbed for each instant at which readings were taken was calculated from the spring elongation measured by the cathetometer and the spring calibration curve.

3. Calculations of the Molecular Weight of the Adsorbate

The molecular weight of the adsorbate was calculated from the number of moles of gas adsorbed and the weight of the gas adsorbed.

Discussion

The research accomplished made it apparent that the molecular weight, proportion, and molecular structure of the mixture components, in addition to the average molecular weight, boiling point of the mixture, and operating pressure, all influence the molecular weight of the adsorbed gas on charcoal at isothermic conditions. From the data recorded, curves showing the variation with time of the molecular weight of the adsorbate were prepared for the 4 systems: ethylene-propane, ethylene-butane, propane-butane, and ethane-propane.

Molecular Weight of Adsorbed Mixture

Fig. 2 presents, as an example, the corresponding curves for the system ethylene-propane, in which the molecular weight of the adsorbate has been plotted against adsorption time. The molecular weight of the adsorbate appears to be always larger than the molecular weight of the unadsorbed mixture. An increase of the molecular weight of the adsorbed mixture becomes appreciable after time zero. This trend starts from the initial molecular weight of gas mixture, at which the molecular weight of adsorbate was extrapolated to time zero, and continues to increase until equilibrium is reached.

A study of Fig. 2, and of curves corresponding to the other 3 systems which are not shown here, reveals that each curve has 2 different slopes connected by an intermediate section that passes smoothly from the first slope to the second slope, as with most of the adsorption-rate curves reported in the literature. This could mean that the controlling factor in the adsorption during the first part of the run is different from that controlling adsorption in the second part. While the free absorbent surface should influence the first part of the run, it seems reasonable to assume that, on the second part of the curve, the further increase in the molecular weight, after the

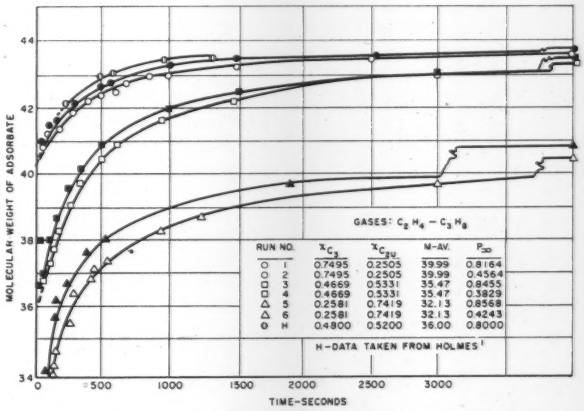

Fig. 2. Rate of change of molecular weight of adsorbate: effect of composition of mixture and pressure.

adsorbing surface has been saturated, is caused by replacement of the lighter molecules by the heavier.

Using the number of moles of gas adsorbed, and the weight of gas adsorbed, the writers calculated the number of moles of each gas adsorbed at each particular time. It was found that the number of gas moles adsorbed of both gases increases with time, until probable saturation of the adsorbent surface; after that, a desorption of the lighter gas takes place, while the heavier gas is slowly adsorbed by the charcoal, until equilibrium is reached. These 2 periods of adsorption correspond to the 2 different slopes of the curves. It is possible that the replacement of lighter molecules by heavier ones takes place also in the first period, but the rate at which the light gas is adsorbed on the free adsorbent surface surpassed the rate of displacement; therefore adsorption of light gas continued to take place as long as there was free adsorbent surface. Holmes[1] also reported this phenomenon of desorption of the lighter gas after a certain time. However, the length of time apparently depends on the rate of adsorption, nature of the gases, and amount of adsorbent.

If the increase of the molecular weight of the adsorbate in the second part of the run occurred by replacement, it would seem possible to find a simple relation between the heavier molecules adsorbed and the lighter ones desorbed. However, earlier researchers have reported that the adsorbing surface of charcoal is not the same for all gases. Because of this fact, together with the difference in affinity and molecular structure, and the size of the molecules, the relation between the adsorbed and desorbed molecules varies in different mixtures.

Influence of Mixture Composition

The curves of Fig. 2 (and those of the other systems investigated) permit also a comparison of the adsorption curves of the same systems when their components are in different proportions. The molecular weight of the adsorbate approaches the molecular weight of the heavier component as equilibrium is approached; this approach naturally is better for mixtures with a higher proportion of the heavier component and equilibrium is reached faster when mixtures of a higher percentage of heavier component are used. This difference in the time taken to reach equilibrium is due to a prolonged replacement time when mixtures with lower percentages of the heavier component are used; but for both cases, the time of the adsorbing section of the run is about the same.

The difference in the length of time to reach equilibrium can be explained on the same basis as replacement of molecules. It will take a longer time to have the same number of strikes of heavy molecules on the charcoal surface when mixtures with lower concentrations of heavy components are used.

For mixtures that have different percentages of the heavier component, the difference in the molecular weight of their adsorbates decreases as equilibrium is approached, as may be seen in Fig. 2. These curves indicate that, despite the large difference in initial mixture composition, the adsorbed gas at equilibrium has a high molecular weight in all cases, with values a little different in each case. When mixtures with 50% of heavier component are used, the adsorbed gas has a molecular weight very close to that of the heavier component. This means that a larger amount of the heavier component in the initial mixture will not make much difference in the molecular weight of the adsorbate, whenever the heavier component constitutes more than 50% of the initial mixture.

Influence of Molecular Weight of Initial Gas Mixture

From a study of Fig. 2 (and data recorded for the other systems), it appears that the molecular weight of the adsorbate increases with the difference between the molecular weights of the component gases of the mixture, even if, in both cases, the average molecular weight of the mixture is the same. When the second component is of a much lighter weight, it is to be expected that a much larger proportion of the heavier component is required to bring up the average molecular weight of the gas mixture; this would justify the findings.

Influence of Pressure

Within the operating pressure range it was hardly possible to have an over-all picture of the influence of pressure on the adsorbed gas. However, Fig. 2 (and other data) permit the comparison of the molecular weight of adsorbed gas when similar mixtures are adsorbed at 2 different operating pressures.

It was found that, for pressures between 0.3 and 0.8 atmospheres, the influence of the pressure on the adsorbed gas is not always in the same direction.

For the systems ethane-propane, propane-butane, and ethylene-propane, the molecular weight of the adsorbed gas seems to decrease with an increase of pressure; but for the system ethylene-butane, the molecular weight increases with pressure. This variation of the molecular weight with the pressure was small, and was observed for mixtures in which both components were in the same proportion. For larger proportions of the heavier component, the molecular weight of the adsorbed gas tends to reach the same value at both pressures at equilibrium conditions.

These findings are in agreement with those of Lewis,[2] who reports, for higher operating pressures, an increase of the mole fraction of the light component on the adsorbent. The discrepancy in the system ethylene-butane could be an experimental error, as the difference between the 2 values of the molecular weights obtained at the 2 different pressures is so very small; however, Holmes[1] whose findings were the same as the writers' for this sys-

(Concluded on page 63)

(1) Holmes, H. W., "The Adsorption of Binary Hydrocarbon Mixtures On Activated Charcoal," M.S. Thesis, University of Washington (1951).

(2) Lewis, W. K., Gilliland, E. R., Chertow, B., and Cadogan, O. P., *Ind. Eng. Chem., 42*, 1319 (1930).

Effect of Fly Ash Characteristics on Collector Performance*

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Fly ash is a generic term used to designate the particulate matter carried in suspension by the effluent or waste gases from furnaces burning fossil fuels. In modern usage the term is most commonly applied to the emission from the burning of pulverized coal. The character and properties of the ash vary widely with such factors as the coal burned, the design and operation of the furnace and auxiliaries, and the steaming rate of the boiler.

Fly ash is a nuisance, an unwanted by-product of the power-generation industry. If permitted to escape in appreciable quantity, it becomes a nuisance to neighboring areas. If removed from the effluent gases by gas-cleaning equipment, it becomes a nuisance to the plant operators because it must then be disposed of, usually as added expense, as it has little or no economic value.

Inasmuch as large quantities of waste gas and ash are emitted from typical modern boilers, and gas-cleaning equipment must be custom-engineered for each installation, the over-all expense of collecting and removing the ash is appreciable. For example, a large boiler rated at 1,400,000 lb./steam/hr. typically will emit 700,000 cfm. of waste gas and 140 tons of ash/day. Under present conditions the capital cost of high-efficiency ash-collecting and handling equipment in this example is of the order of $5 to $6/kw. generating capacity, or about 3 to 4% of the total capital investment. The operating cost, including removal of the collected ash from the plant, may range from $0.20 to $0.40/kw.-yr.

It is apparent that fly ash is not only a nuisance, but involves considerable expense for its collection and disposal, without contributing to the efficiency or revenue of the plant, with the one exception of reducing abrasive wear on induced draft fans, which may be an important consideration in some cases. However, high-efficiency gas-cleaning equipment for the removal of fly ash from stack effluents has been incorporated in pulverized-coal-fired boilers almost from the beginning of this method of firing and is now an integral component of virtually all such boilers.

The effective collection of fly ash involves technical, space, and economic factors. The technical factors are in large degree governed by the characteristics or properties of the fly ash and cannot be disassociated from them. Also, the space and economic factors are in part related to the fly ash properties in that fly ashes having characteristics favorable to collection permit the use of smaller and cheaper collector equipment. However, in the case of new boiler installations it is generally not possible to predict the fly ash properties with any degree of certainty, so that it may be impossible to take full advantage of favorable ash properties.

The continuing trend toward higher-output boilers, the use of higher-ash coals, and the requirements for higher-efficiency collectors, have placed increasingly heavier demands on the fly ash-collection equipment. For example, collection efficiency requirements have risen from the order of 90% for earlier installations to 95 to 98% for installations made during the past few years. Fundamental and practical improvements in collector design have kept pace with the heavier demands to a considerable degree, but the unpredictability of fly ash characteristics is in many cases a complicating factor.

Progress has been made in relating fly ash characteristics to coal type and composition, and to furnace design and operation. However, these studies involve a large number of variables and are long-range in character. The approach of making collector performance independent of ash characteristics is attractive but unfortunately can be realized only to a limited degree. Ultra-conservative design is of course limited by the inherent economic factors. Continued basic research directed toward better understanding of the critical performance factors and improvement in fundamental design of collectors appears to be the surest method of successfully meeting the ever-increasing demands of fly ash collection.

This paper surveys and analyzes what is probably the most important phase of the collection problem, namely, the effect of the properties of the fly ash itself on collector design and performance. That there exists a close relationship between fly ash properties and collector technology is of course well known. For example, particle size imposes a basic limitation on inertial collectors, while electrical resistivity is a fundamental factor in the performance of electrical precipitators. A broad range of accumulated experience and knowledge now exists on these and other related factors and forms the basis of the paper. The primary objectives are:

1. To describe the important properties of fly ash;
2. To indicate the dependence of these properties on such factors as coal burned and furnace design and operation;

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3. To show the intimate relationship between fly ash characteristics and collector performance;
4. To bring out the principles and methods used in precipitator design and operation to overcome adverse characteristics of fly ash; and finally
5. To indicate future trends and advances which may be expected in this field.

The paper is sub-divided under several main sections as follows: Description and Properties of Fly Ash, Precipitator Performance, Precipitator Design, Combination Inertial-Electrostatic Collectors, and Conclusion. Inertial collectors are not discussed separately because virtually all gas-cleaning installations in modern generating stations are either electrostatic or combination inertial-electrostatic systems. The scope is intended to be broad, but with sufficient detail to provide an integrated picture of the present state of knowledge in this field. Emphasis is placed on fundamental factors and relationships wherever possible, rather than on isolated empirical observations or results.

Description and Properties of Fly Ash

Physical Appearance

Fly ash in the bulk or collected state varies widely in appearance. It is granular or powdery in structure, the grains or particles ranging from very fine to very coarse, depending on the sample and source. The color varies from a light tan or light gray through various shades of gray to black or almost black. The tan shade is usually associated with the presence of iron oxide, while the dark shades are associated with carbon or combustible material, or in some cases with magnetic iron oxide.

Fine fly ash has a pronounced tendency to form stable agglomerates or masses and also to adhere to surfaces. Coarse fly ash, on the other hand, acts more like sand and does not exhibit these cohesive and adhesive tendencies.

Freshly collected, hot fly ash usually shows liquid-like properties. For example, it tends to flow like water and also will exhibit surface waves when disturbed. As the ash cools, it tends to compact and to lose these liquid properties. Some kinds of fly ash will cement and form semi-hard accretions on surfaces if allowed to become moist or slightly wet.

Under miscroscopic examination fly ash is seen to be composed of particles having a variety of shapes and covering a wide range of particle size from less than 1 μ to over 300 μ. Most of the small particles up to about 20 to 30 μ are translucent hollow spheres (cenospheres) or fragments. The carbon particles generally range in size from about 10 μ to over 300 μ. They vary in shape from slivers to sponge- or lace-like particles. The latter are usually large and of low density, having a characteristic coke-like micro-structure; they are commonly referred to as grit. Some fly ashes contain relatively large, white particles which may originate from foreign mineral matter in the coal or, in some cases, from agglomeration of finer ash particles while still in a fused state. Photomicrographs of typical fly ashes are shown in Fig. 1.

The percentages of these constituents present in fly ash vary widely from sample to sample, depending on such factors as coal burned and furnace operation. It is apparent that fly ash is a heterogeneous and highly variable material, and may have widely different physical and chemical properties from plant to plant, or even from day to day in the same plant.

Particle Size

Particle-size examination of fly ash by means of optical and electron microscopes shows particles present from less than 0.01 μ to several hundred μ in diameter. For most fly ashes, over 90% by weight will be in the region between 1 and 100 μ, with the median size commonly in the range of 5 to 20 μ. Inasmuch as the particle shape of fly ash is heterogeneous and varies with the sample and as particle size for non-spherical particles is usually expressed in equivalent diameters, the measured particle size distribution will depend in part on the method of analysis used. Therefore these methods must be considered.

There are no generally accepted standard methods for determining particle size of fly ash. Sieve analysis is widely used for the coarser fractions above 325-mesh

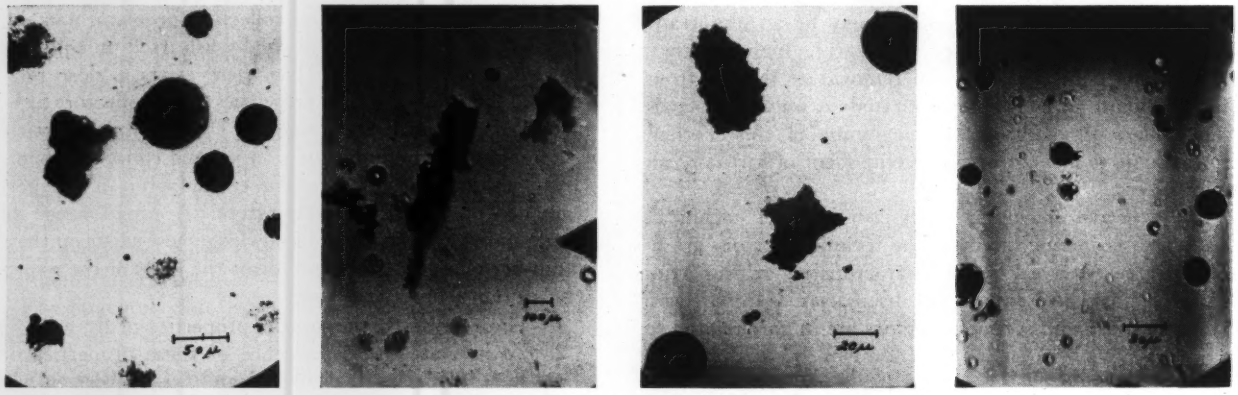

Fig. 1. Photomicrographs of Fly Ash.

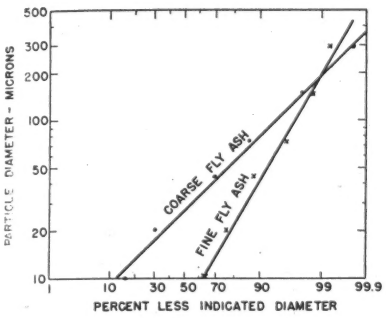

Fig. 2. Log-Probability Particle-Size Plots for 2 Typical Fly-Ash Samples.

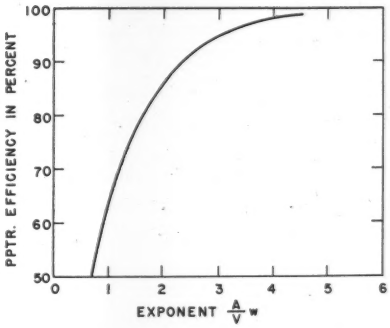

Fig. 4. Variation of Precipitator Efficiency with the Exponent $\frac{Aw}{V}$ in Basic Precipitation Equation (1).

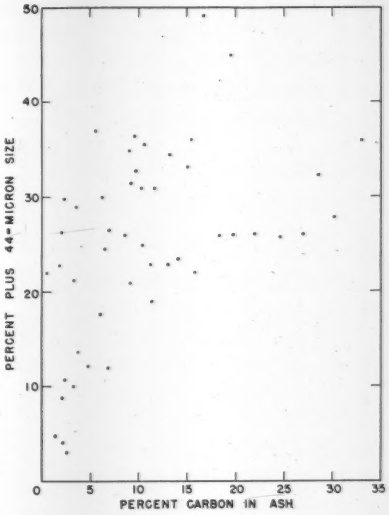

Fig. 3. Carbon Content versus Percentage of Plus 44 μ Particles for 48 Representative Fly Ashes.

screen-size, corresponding to approximately 44 μ particles. There are a number of methods available for determining the finer or subsieve-size particles. These include sedimentation in liquids, elutriation in air, microscopic count, and centrifugal or inertial classifiers, as well as a number of other methods. None of these methods is completely satisfactory, and each has its own advantages and disadvantages. There are many literature references[1] on this subject which should be consulted for critical comparisons of the various methods.

A further difficulty in particle size determination is the procurement of representative samples from the field. Grab or spot samples from flue settlings or collector hoppers are usually unreliable and give distorted pictures of particle size. For example, flue settlings will nearly always be coarser than the actual ash. The most satisfactory method of procuring samples is by means of a many-point traverse of a relatively straight section of the gas flue, using either the Brady-filter-thimble method or a high-volume type sampler. The filter-thimble method is usually limited to ash sample quantities of only a few grams, which in turn limits the methods of particle size analysis which may be used to those requiring relatively small samples. On the other hand, the much larger ash-sample quantities collected by high-volume-type samplers permit a wider choice of particle-size-analysis methods.

Comparisons of the particle-size results obtained independently by different laboratories on samples of the same ash may show substantial differences, particularly for the subsieve-size range. It is obviously essential that particle-size information on fly ash always be prefaced by a statement of the method of analysis used as well as the source and method of procuring the original sample from the plant. Under present conditions, statements or guarantees of collector performance based on particle size have no definite meaning unless the ash-sampling and size-analysis methods are specifically included.

A summary of fly-ash-particle-size data for representative modern power plants is given in Table I. These figures were compiled from measurements made in our laboratory during the past few years. The field samples were obtained by the Brady filter-thimble method in accordance with ASME standards.[2] The plus 44-μ fractions were determined by sieve analysis using 3-in.-diameter U.S. Standard screens. The subsieve or minus 44-μ fractions were determined by iterative sedimentation in kerosene or methyl alcohol, with particle diameters calculated from Stokes' law.

Observe that all samples but one are relatively fine, ranging between about 45 to 85% less than 10 μ by weight. The one coarse sample (No. 10) was from an

(1) Dallavalle, J. M., "Micromeritics," Pitman Publishing Company, New York, N. Y., 1948.

TABLE I
Summary of Fly-Ash Particle-Size Data for Representative Modern Power Plants.

Sample No.	Diameter of Particles in Microns						
	—10μ	—20μ	—44μ	+44μ	—74μ	—149μ	—297μ
1[a]	81.3%	90.4%	91.1%	8.9%	96.8%	99.1%	99.3%
2	63.4	81.4	85.7	14.3	94.3	98.5	99.7
3	45.2	64.1	70.0	30.0	85.1	94.6	99.0
4	48.2	67.6	75.0	25.0	85.4	93.8	98.2
5	60.4	82.7	91.1	8.9	.....	.....	.....
6	63.1	85.1	89.1	10.9	95.4	98.6	99.6
7	57.9	83.4	87.7	12.3	94.6	98.2	99.6
8	57.1	72.4	75.4	24.6	90.3	99.1	99.9
9	68.5	82.5	84.1	15.9	91.6	97.3	99.6
10[b]	15.5	31.0	68.8	31.2	86.7	97.8	99.8
11[c]	86.8	94.3	97.0	3.0	99.0	99.7	99.9
12	63.0	77.0	88.1	11.9	96.0	98.5	99.3
Average	59.2%	76.0%	83.6%	16.4%	92.3%	97.7%	99.4%

(a) Anthracite coal, very fine pulverization.
(b) Old-type boiler for central steam-heating plant. Figures given for contrast.
(c) Cyclone-type furnace.

(2) Am. Soc. Mech. Engrs., "Test Code for Dust-Separating Apparatus, PTC 21-1941.

older boiler in a steam-heating plant. The sample from the cyclone type furnace (No. 11) and from a plant burning anthracite coal (No. 1) are seen to be extremely fine, in the range of 80 to 87% less than 10 μ by weight. The remaining samples are from boilers burning bituminous coals, and with the one exception previously noted are relatively fine, with values of the minus 10-μ fraction between about 45 and 70%. We may conclude that modern boilers burning pulverized coal emit relatively fine fly ash.

It has been found that the particle size distribution for many fly-ash samples closely follows the so-called log-probability law.[1] This is illustrated in Fig. 2, which shows the particle-size distribution for two typical fly-ash samples. Sieving was used to determine the plus 44-μ fractions, while sedimentation in methyl alcohol was used for the minus 44-μ or subsieve fractions. The logarithm of the particle diameter is plotted against the cumulative percent present on a probability integral scale. It is seen that the experimental points fit straight-line plots very well. This method of plotting and presenting particle-size data is useful and convenient and serves as a check on the accuracy of the measurements. It also permits interpolation between points as well as limited extrapolation beyond the experimental range covered.

Carbon Content and Particle Size

The presence of carbon in fly ash indicates incomplete combustion in the furnace and therefore loss of fuel. For example, if we assume a coal with an ash content of 10%, and the fly ash contains 10% carbon, the loss of fuel will be about 1%. This represents a significant cost item in the coal bill. It is therefore desirable to reduce the carbon lost with the ash to the lowest practicable amount.

Factors which influence the degree of carbon in the ash include character of the coal, fineness of pulverization, burner design, location and adjustment, furnace temperature, coal-feed rate, and amount of excess air. In general, the carbon in the ash tends to increase roughly in proportion to the fixed carbon in the coal. Fineness of pulverization is a very important factor, particularly with coals having relatively high fixed-carbon content. Burner design, location, and adjustment are important because these factors largely determine the completeness of combustion. For example, it is frequently found that changing the tilt of burners can increase or decrease the carbon in the ash by a factor of 2 or more. Load swings on the boiler may also influence carbon in the ash due to transient maladjustments.

Carbon is usually present in fly ash in the form of irregularly shaped particles, ranging in size from about 10 μ to over 300 μ. The larger particles have a porous or coke-like structure. The smaller particles may be fragments of the coke-like particles or in some cases may be fused in a matrix of inorganic matter. Walker[3] in his survey of fly ash reports carbon content of ash ranging between 0.37 to 36%. Our measurements on over 100 different fly ashes show figures of from virtually zero to 55%. These are extremes and are not typical of the majority of fly ashes. Representative figures for most ashes are about 2 to 20%, with an average of about 10%.

The carbon or combustible content of fly ash is usually determined by igniting the ash in a muffle furnace at a temperature of 700-750° C. for a period of ½ hour. Qualitative estimates of carbon content may be made by microscopic examination, or in some cases by the blackness of the bulk ash.

There is a rough correlation between the percent carbon present and the coarseness of fly ash. This is shown graphically in Fig. 3. In general, a relatively high carbon content of higher than about 10 to 15% corresponds to a fairly coarse ash, while a lower carbon content tends to be associated with a relatively fine ash. However, it should be noted that the correlation is only partial, and that the carbon content of fly ash is not by itself a safe index of degree of fineness. On the other hand, the ash from a given boiler may show a much closer relationship between carbon content and degree of coarseness.[4]

With modern boilers the tendency is toward relatively low carbon content in the ash, with values usually less than 10% and frequently less than 5%. Values of carbon content of only 1 or 2% are not uncommon.

The carbon in ash is sometimes confused with the so-called grit. Grit refers to the coarser particles, and is somewhat a matter of definition. Grit may be defined as that portion of an ash retained on a 200-mesh (74-μ) sieve. These larger particles are frequently carbonaceous, but may also be inorganic or mineral matter. Further, an appreciable or even a major portion of the carbon present in an ash may be substantially smaller than 200 mesh. Therefore, it is in general incorrect to designate the carbonaceous particles as grit even though some of them may fit this category.

Density

The density of fly ash depends primarily on its particle size, particle structure, and carbon content. In general, the relatively large, coarse particles containing a high percentage of carbon have a low density. These particles commonly have a porous or lace-like structure and result from the partial combustion of the pulverized coal. It appears that the volatile portion burns out, leaving coke-like particles which are black in color. These particles have low densities of the order of 0.6 to 1.0 gm./cm.^{3}

The finer particles of the ash, which tend to be low in carbon content, have a much higher density, usually in the range of 1.5 to 3 gm./cm.^{3} These particles do not exhibit the porous structure of grit, although many of them

(1) See footnote 1, p. 39.

(3) Walker, H. S., "The Present and Future Magnitude of the Pulverized-Coal Fly-Ash Disposal Problem," Paper No. 49-A79. Presented at the Fly-Ash Symposium, ASME Annual Meeting, New York, N. Y., November 27-December 2, 1949.

(4) Bauman, H. A., "Air Pollution Prevention in Electric Generating Stations," *Electrical Engineering, 72,* No. 3, 200-204 (1953).

TABLE II
Densities of Particle-Size Fractions for a Typical Fly Ash.

Particle-Size Fraction	Percent Present	Density gm./cm.³	Bulk Density	
			gm./cm.³	lb./ft.³
Total sample	100	1.75	0.58	36
−44 μ	78	1.78	0.60	37
44 to 74 μ	10	1.70	0.44	27
74 to 149 μ	8.3	1.60	0.38	24
149 to 297 μ	3.6	1.57	0.25	16
+297 μ	0.1	1.02	0.21	13

may be hollow spheres or cenospheres. The large difference in density and structure of the fine and gritty particles frequently tends to produce a stratification or separation of the particles in the gas. The large, gritty particles have very low adhesive or cohesive characteristics and are therefore easily redispersed into the gas stream.

The variation in density with particle size for a typical fly ash from a modern boiler is shown in Table II. Also given are the corresponding bulk densities and carbon contents of the size fractions. The bulk density of fly ash is usually of the order of 30 to 50 lb./ft.³, but may be as high as 90 lb./ft.³ Freshly collected ash in the hot state is normally very fluid, and has a somewhat lower density than cold ash. The fresh ash is aerated, probably by the exposure of the individual particles to the gas and adsorption of gas layers on the particles. With standing and cooling, de-aeration tends to occur and the ash compacts and becomes less fluid.

Concentration

The amount of fly ash carried in the effluent gas from a furnace depends on several factors. Chief among these are the ash content of the coal, boiler design, and boiler steaming rate. It is clear that the ash emission will be approximately proportional to the ash content of the coal, other conditions remaining fixed. Therefore, high-ash coals will in general produce high concentrations of ash, while boiler design and operation determine the percentages of ash retained in the furnace and emitted in the flue gas.

Coals encountered in practice have ash contents ranging between about 5 and 25%, with an average value of 10 to 15%. Since the higher-ash coals in general have a lower heating value, a greater weight of such coal must be burned to obtain a given heat output. This factor also tends to increase the emitted ash with high-ash coals.

As an example of the total amount and concentration of ash to be expected in a typical case, consider a modern boiler operating at a rated load of 875,000 lb. steam/hr. and burning 98,500 lb. of 11%-ash coal/hr. The amount of flue gas measured at the air-preheater outlet in this example was 413,000 cfm. at 260° F. Hence, if all of the ash were emitted, the concentration would amount to

$$\frac{(98{,}500 \text{ lb. coal/hr.})\ (0.11)\ (7000 \text{ grains})}{(60 \text{ min.})\ (413{,}000 \text{ cfm.})}$$

$$\left.\begin{array}{l} = 3.05 \text{ gr./ft.}^3 \text{ at } 260° \text{ F.} \\ = 4.5 \text{ gr./ft.}^3 \text{ at } 32° \text{ F.} \end{array}\right\} \text{ based on carbon-free ash.}$$

$$= 5.0 \text{ gr./ft.}^3 \text{ at } 32° \text{ F.,}$$
including the 10% carbon present in the ash.

The concentration actually measured in this example was 3.3 gr./ft.³ at 32° F., of which 10% was carbon. Consequently, (0.90) (3.3)/4.5 or 67% of the ash was being exhausted from the boiler in the form of fly ash.

The retention of ash in the furnace usually will be in the range of 20 to 40%, although values of 70% or more sometimes occur. These figures apply to ordinary furnaces. In the case of cyclone-type burners, the ash retention in the furnace is much higher, of the order of 80 to 85%. This greatly reduces the amount of ash to be removed by the collecting equipment, but the extreme fineness of the emitted ash requires the use of electrostatic precipitators, even though required collection efficiency may be only 80%.

A survey of field measurements of actual fly-ash concentrations covering a large number of power plants shows figures ranging between a minimum of about 0.3 gr./ft.³ and a maximum of about 15 gr./ft.³, reduced to a gas temperature of 32° F. These represent extreme limits and are not typical of most plants. For the majority of plants the concentration ranges between about 2 to 8 gr./ft.³, with an average of 3 to 4 gr./ft.³ For large, modern boilers this means a total daily emission of the order of 100 to 200 tons/day which must be handled by the dust-collector and disposal system.

Cohesive and Adhesive Properties

The cohesive and adhesive properties of fly ash are important for collection by electrostatic precipitators in which the ash forms in compacted layers on the electrode surfaces. These collected layers are typically about 0.5 in. thick, but may in some cases build up to 1 in. or more in thickness. Some of the collected ash falls into the hoppers either because of the mechanical vibrations frequently present in plant structures or of its own weight, but rapping or jarring of the electrodes is usually necessary to effectively remove the collected ash layers. The ash generally breaks away in isolated patches, so that the collecting-plate surfaces normally present a somewhat spotty appearance.

It is well known that fine solid particles tend to cohere and to form agglomerated masses which have a small but definite stability. The coherence of the particles is caused by molecular attractive forces at the points of contact of the particles. The degree of coherence is appreciable only for relatively fine particles of less than about 20 to 40 μ. Coarse or granular particles such as sand, for example, do not cohere in the dry state. On the other hand, fume particles, which typically are less than 1 μ in size, usually show a high degree of coherence. The coherent properties of fine particles have been treated theoretically with re-

sults roughly in agreement with observations.[5]

The adhesion of particles to the collecting electrodes is also the result of molecular attractive forces, and, similar to cohesion, the adhesive forces are larger for fine particles. Thus, the adhesion and retention of the collected layers of ash on the electrodes is determined basically by particle size, and increases with decreasing particle size. However, other factors such as particle shape and composition also influence the adhesion and cohesion of particles. The presence of condensed moisture, with possible cementing effects, can also profoundly influence the build-up of particles on electrodes and other surfaces.

In electrical precipitators an additional retention force of major importance is produced by the rain of the corona ions on the collected dust layers. These ions tend to charge the collected particles in such a manner that they are attracted to the collecting plates by relatively strong electric forces. Further, any particles that succeed in escaping from the collected layers of ash tend to be immediately recharged electrically by the corona ions and forced back to the collecting plates. The particle-retaining force of the corona current increases with the electrical resistivity of the particles and with the strength of the current. Hence, there frequently is an advantage in operating precipitators, particularly the outlet sections, at relatively high-corona current densities.

Agglomerated masses of particles removed from the electrodes by rapping fall into the hoppers by the force of gravity. These agglomerated masses are bound together by the molecular cohesive forces. It is essential for best performance that these falling agglomerates be relatively stable and fall with as little loss of particles as possible. If the falling agglomerates have little coherence, some of them may break up and be redispersed in the gas stream, thus partially nullifying the collecting action of the precipitator.

The presence of coarse particles tends to reduce the cohesive and adhesive forces and, therefore, the agglomerating effect which holds masses of fine particles together. Excessive amounts of coarse, gritty particles in an ash make the ash difficult to hold on the collecting plates and also lead to loose, unstable agglomerates when the plates are rapped.

Since the coarser, gritty material is likely to be comprised of partially burned coke-like particles of relatively low density and high electrical conductivity, the situation may be further aggravated as these particles tend to float along with the gas stream and have only a small binding force to the electrodes. Under these conditions there may be a disproportionate loss of the so-called grit. The effect may be successfully countered by the use of pocket-type collecting electrodes, lower treatment velocities, inertial collectors, or by better combustion in the furnace. However, the elimination of all coarse particles above about 10 to 20 μ may in some cases make it difficult to remove the ash from the collecting plates of a precipitator. There also will be a much greater tendency for the particles to build up on the discharge wires. Thus a very fine ash containing no coarse particles presents a more difficult rapping problem.

Electrical Properties

Since electrical properties of fly ash are fundamentally related to precipitator performance, they are described and discussed under that heading.

Chemical Composition

Fly ash is composed chiefly of silicates, oxides, sulphates, and carbon. In addition to these main constituents, there are a large number of rare elements present in minute quantities. The composition, or relative percentages of these constituents, covers a wide range for different ashes.

A Bureau of Mines publication[6] lists the typical limits of coal-ash analysis as shown in Table III. Further data have been reported by Walker[3] on the chemical analyses of ash from 46 public utilities. The percentage ranges for each element as given by Walker are shown in Table IV. More detailed analyses, as shown in Table V, were obtained by Davis[7] a number of years ago in connection with an investigation of the use of fly ash in concrete.

The major constituents of most fly ashes as shown by these analyses are silica, alumina and iron oxide. The first two are present primarily as silicates, which give fly-ash particles their typical, glassy appearance. The iron oxide may be present as Fe_2O_3, which in appreciable amounts imparts a typical tan or reddish tinge to bulk fly ash, or it may be present as Fe_3O_4 or magnetite, in which case the fly ash may have marked magnetic properties.

Carbon or combustible material also may be a major constituent of some fly ashes. The carbon, of course, is not strictly ash, but rather the product of incomplete combustion, and represents an undesirable loss of fuel. The effect of carbon on ash is discussed in the sections on particle size and electrical properties.

The water-soluble portion of fly ash, although usually a small percentage, is of great importance in electrical

TABLE III
Coal Ash Analysis Limits (Bureau of Mines).

Constituent	Percent
Silica	30-60
Aluminum oxide	10-40
Ferric oxide	5-30
Calcium oxide	2-20
Magnesium oxide	0.5-4
Titanium oxide	0.5-3
Alkalies	1-4

(3) See footnote 3, p. 40.

(5) Lowe, H. J., and Lucas, D. H., "The Physics of Electrostatic Precipitation," *British Journal of Applied Physics*, Supplement No. 2, pp. S40-S47 (1953).

(6) Fieldner, A. C., Rice, W. E., and Moran, H. E., "Typical Analyses of Coals of the United States," Bur. Mines Bulletin 446 (1942).

(7) Davis, R. E., "Properties of Cements and Concretes Containing Fly Ash." Report to Research Corporation, University of California, 1938.

TABLE IV
Chemical Analysis of Ash from 46 Public Utilities (Walker).

Constituent	Percent
Carbon as C	0.37 - 36.2
Iron as Fe_2O_3 or Fe_3O_4	2.0 - 26.8
Magnesium as MgO	0.06 - 4.77
Calcium as CaO	0.12 - 14.73
Aluminum as Al_2O_3	9.81 - 58.4
Sulphur as SO_3	0.12 - 24.33
Titanium as TiO_2	0.50 - 2.8
Carbonate as CO_3	0.05 - 2.6
Silicon as SiO_2	17.3 - 63.6
Phosphorus as P_2O_5	0.07 - 47.2
Undetermined	0.08 - 18.9

precipitation because of its effect on the electrical conductivity of the particles. Research has shown that the conductivity of fly ash as well as that of many other inorganic or mineral particles is due primarily to adsorbed surface layers of certain chemical agents. In many cases these agents occur naturally as a result of either the source or process by which the particles are formed. A deficiency of these agents results in semi-insulating or high-resistivity particles which, as explained in the section under electrical properties, usually cause trouble in the electrical precipitation process.

In the case of fly ash, the effective conductivity agent appears to be sulphate, or in some cases free sulphuric acid, formed on the surfaces of the particles by adsorption of SO_3 from the flue gas. The water-soluble sulphate content of fly ash is found to vary from less than 0.1% up to several percent, depending on the coal burned and furnace operation. The critical lower value of sulphate for adequate conductivity of fly ash appears to be approximately 0.5%. Most fly ashes are above this value in sulphates, but a few are below it and therefore tend to cause difficulty in electrostatic collection. This phase is treated more fully in the section under electrical properties. The purpose here is to indicate the close relationship between the chemical and electrical properties of fly ash.

Optical Properties

The optical properties of suspended particles have no direct bearing on collector performance, but nevertheless are important because of their relationship to the visual appearance of stack emissions. Fine particles suspended in gases and exposed to a light beam will scatter the light in directions other than that of the original beam and will also obscure or darken the light as viewed toward the light source. The visibility of stack emissions is due to both these effects.

It has been shown both theoretically and experimentally that the light-scattering and obscuring effects increase with the specific surface of the particles and the size or thickness of the stack plume. The specific surface is defined as the total exposed surface area of the particles per gram of dust or dispersoid. It is a function of particle size and increases rapidly with decreasing size of particles. For fly ash, the specific surface usually will be between about 2,000 and 15,000 $cm.^2gm.$ The finer ashes emitted by most modern boilers have relatively high specific surfaces and therefore are much more effective in their light-scattering and obscuring properties. The larger gas flows associated with large boilers also contribute to increased visibility of the emissions.

Removing the coarser fractions of an ash usually will not appreciably reduce the visibility of stack emissions. For example, an inertial collector which removes 75% of the ash will in general only slightly improve stack discharge appearance. The finer particles below about 10 or 20 μ are not collected, and it is these particles with their high specific surface which cause most of the vis-

TABLE V
Chemical Analysis of Ash as Given by Davis.

Fly Ash Number	Chemical Analysis of Ash as Collected, Except as Noted, Figures in Percent												
	SiO_2	FeO[a]	Fe_2O_3	Al_2O_3[b]	TiO_2	CaO	MgO	SO_3[c]	H_2O (240° F.)	CO_2	Na_2O	K_2O	Ign. Loss
1	39.18	2.76	10.55	27.77	1.19	1.22	0.56	0.58	0.44	0.00	0.39	1.14	14.66
2	44.10	4.27	18.99	20.85	1.11	4.00	0.79	1.37	0.36	0.01	0.58	1.53	1.55
3	44.18	4.23	17.45	16.44	0.83	7.14	0.92	2.34	0.32	0.16	2.17	1.82	1.50
4	41.70	4.23	11.77	27.88	1.21	3.44	0.89	0.92	0.27	0.07	0.67	2.56	3.91
5	40.26	2.33	9.92	29.74	1.47	1.60	0.62	0.89	0.53	0.05	0.43	1.11	11.87
6	35.24	2.85	7.74	22.87	1.27	10.59	1.82	1.50	0.15	0.32	1.03	1.12	13.16
7	34.68	4.06	14.30	21.52	0.97	2.80	0.55	1.42	0.57	0.19	0.47	1.20	18.12
8	49.00	2.07	3.86	27.53	1.45	5.36	0.86	0.42	0.09	0.17	0.73	2.09	6.56
9	47.82	2.16	6.98	25.57	1.19	2.48	0.79	0.46	0.14	0.16	0.66	1.85	9.82
10	47.00	2.81	9.99	19.94	1.01	5.02	0.92	1.76	0.41	0.06	0.92	1.89	7.89
11	30.32	1.58	7.00	18.54	0.90	8.32	1.91	1.27	0.08	0.13	0.90	1.29	27.89
12	37.84	2.35	9.96	24.41	1.00	1.68	1.15	1.28	0.13	0.00	1.15	1.97	17.05
13	40.40	1.28	3.91	30.65	1.04	1.78	1.17	0.97	0.13	0.01	1.03	1.82	15.30
Average	40.90	2.84	10.19	24.13	1.13	4.26	1.00	1.17	0.28	0.10	0.86	1.65	11.48

(a) Total Fe and ferrous compounds as FeO.
(b) Includes all of NH_3 group, except Fe and Ti.
(c) Total sulphur and compounds as SO_3.

ibility. Electrostatic precipitators are less selective than inertial separators in the size of particles collected, but even for these, 75% removal efficiency will not show much improvement in stack appearance unless the initial ash concentration is very low.

We have made theoretical studies of the fly ash concentrations which are necessary to produce an essentially clean or invisible stack discharge for typical cases. The results indicate that the ash concentration must be reduced to the order of 0.02 to 0.03 gr./ft.^{3} in order to insure an essentially clean stack discharge. For the average fly ash case this corresponds to a collector efficiency of about 99%, assuming an inlet concentration to the collector of about 3 gr./ft.^{3} Field observations on actual stack discharges appear to support this conclusion.

Precipitator Performance

Before discussing the relation of precipitator performance to fly-ash properties, it is necessary to review briefly the fundamentals of the electrical precipitation process. Basically, the process comprises charging the suspended particles in the corona discharge, subjecting the charged particles to an electric field which causes the particles to migrate to collecting electrodes, and then removing the collected particles in the form of relatively large agglomerated masses to receiving hoppers.

It has been shown by theory, experiment, and field experience that the collection efficiency of a precipitator is governed by 2 rather simple equations.[8-9] These are:

$$\text{Collection efficiency} = \eta = 1 - e^{-\frac{Aw}{V}}, \text{ and} \qquad (1)$$

where

$$\text{Migration velocity or precipitation rate of particles} = w = \frac{aE_oE_p}{2\pi\theta} \qquad (2)$$

A = effective collecting electrode area of precipitator,
V = gas flow rate through precipitator,
e = base of natural logarithms = 2.718 . . .,
a = particle radius,
E_o = strength of field in which particles are charged,
E_p = strength of field in which particles are collected, normally the field close to the collecting plates, and
θ = viscosity or frictional resistance coefficient of the gas

Equation (1) shows that precipitator efficiency increases with increasing value of the exponent $\frac{Aw}{V}$, as illustrated in Fig. 4. Further, it may be noted that efficiency increases with electrode area A (precipitator size) and with migration velocity of particles w, but decreases with gas flow rate V (cfs or cfm). Equation (2) shows that the migration velocity or precipitation rate of the particles w increases with particle size a and with the precipitator fields E_o and E_p, but decreases with gas viscosity θ. Note that precipitation rate w is particularly sensitive to the electrical conditions in the precipitator, since the electric fields appear as a product, and a small increase in these fields means a much larger increase in w.

Calculated values of the precipitation rate w for representative fly-ash precipitators based on equation (2) give values 2 or 3 times those actually obtained in practice from equation (1). The discrepancy may be explained by the presence of uneven gas flow, re-entrainment of collected particles, and other factors which cannot be included in the idealized theory. However, for engineering purposes it is found practical to use the fundamental precipitation formula (1), with modified values of precipitation rate w. These modified values of w are determined from actual field experience with fly-ash-precipitator installations. In essence, the fundamental equations are used as the basis for analyzing and comparing field precipitator performance and for calculating new designs from previous experience. The practical range of values for precipitation rate w for the majority of fly-ash precipitators is from about 0.2 to 1 ft./sec. The value of w is a direct measure of the performance for any given installation. High values of w represent good performance, and vice versa.

With this brief summary of fundamentals as a background, it becomes possible to analyze the effects of fly ash properties on precipitator performance from a fundamental rather than from a merely empirical point of view.

Effect of Particle Size

Equation (2) for the precipitation rate w shows that performance increases directly with the particle radius or particle size. Strictly speaking, the formula applies accurately only to spherical particles. However, for irregularly shaped particles an equivalent particle size may be used with sufficient accuracy for the present discussion.

Although large particles are easier to precipitate than smaller particles, in the case of fly ash it is found that particles larger than about 74 μ, frequently referred to as grit, may be difficult to hold or retain on the collecting plates on account of the windage effect of the gas stream. As previously noted, these large or gritty particles usually have a porous, coke-like structure of low density and exhibit low cohesive and adhesive forces. For these reasons, as well as their relatively large surface area, they are easily re-entrained in the gas stream.

Successful methods of dealing with the grit problem in fly-ash precipitators include the use of pocket- or shielded-type collecting electrodes, low precipitator-gas-velocities and auxiliary mechanical collectors, which are efficient in removing large particles. Most fly-ash precipitators today incorporate one or more of these methods of grit control.

A further influence on precipitator performance is through the cohesive and adhesive properties of the ash which depend to a considerable degree on particle size

(8) White, H. J., Roberts, L. M., and Hedberg, C. W., "Electrostatic Collection of Fly Ash," *Mech. Eng.*, 873-880 (November 1950),

(9) White, H. J., "Fundamental Performance Factors in the Electrical Precipitation Process," Presented at Am. Chem. Soc. Meeting, New York, N. Y., September 16, 1954.

We have indicated that fine particles have relatively strong cohesive and adhesive tendencies, whereas large particles do not. Further, in a mixture of fine and coarse particles, the over-all effect of the coarse particles, if present in sufficient amount, is to produce an ash which is difficult to retain on the collecting electrodes and which also is difficult to transfer to the hoppers without incurring appreciable losses of material.

Effect of Density

Density of the particles is not a fundamental consideration in the electrostatic precipitation process. However, density can sometimes exert a secondary influence because light, fluffy formations of particles on the collecting plates are harder to remove and tend to fall more slowly to the hoppers, with resultant increased probability of re-entrainment in the gas stream. On the other hand, relatively dense particles which form stable agglomerates can be rapped from the plates and transferred to the hoppers with very low losses. The bulk density of fly ash is rather high, so that in general this factor is favorable for electrostatic collection.

Effect of Particle Concentration

Particle concentration does not appear in the basic precipitation equation and is not a fundamental factor in precipitator performance for the range of concentrations usually encountered in practice. However, particle concentration may in some cases exert a secondary influence on precipitator operation. This comes about through the electrical space-charge effects which occur when dealing with relatively high concentrations of fine particles. These space-charge effects alter the electrical characteristics and operation of the precipitator in the direction of producing lower currents and higher voltages. This effect in the case of fly-ash precipitators is generally beneficial because the higher voltages tend to improve performance. In any case, the electrical space-charge effect is important only in inlet sections of precipitators, where the particle concentrations are highest.

Particle concentration also may exert another secondary influence, because high concentrations mean a greater mass of materials to be collected and disposed of. Thus particle build-ups on the electrodes will in general be larger for high concentrations of particles, and rapping of the electrodes may be more critical. However, these factors will not as a rule have any appreciable effect on performance provided that the precipitator design and rapping system are adequate to handle the material collected.

Effect of Electrical Properties

As might be expected, the electrical properties of fly ash are important in the electrostatic collection process. The 2 electrical properties of major importance are the electrical conductivity or resistivity and the dielectric strength of the bulk ash.

For effective operation, a small but definite electric current in the form of corona gas ions flows between the high-tension discharge electrodes and the collecting electrodes. This current must pass through the layers of collected ash which normally coat the plates. Therefore, the ash must be able to conduct the corona current to the grounded metal surfaces of the plates. The electrical conductivity required is very small, of the order of 10^{-10} mho. In practice, it is usually more convenient to express this in terms of resistivity, which is the inverse of conductivity. Thus the ash resistivity should be less than about 1×10^{10} or 2×10^{10} ohm-cm. for satisfactory operation of the precipitator. Higher resistivities tend to cause excessive sparking, limit the voltage which can be used, and result in subnormal performance of the precipitator. This is implicit in equation (2), which shows that precipitation rate w (and therefore precipitator performance) will fall off rapidly with decreasing electrical fields and voltages.

Measurements made on a wide variety of fly ashes under actual field conditions show normal values of resistivity ranging between 10^8 and 10^{10} ohm-cm. However a limited number of ashes are found to be in the region of 2×10^{10} ohm-cm., where precipitator trouble is a possibility, and a few in the region of 5×10^{10} ohm.-cm. where trouble is virtually certain. Typical field values of fly ash resistivity are shown in Table VI.

Research studies[10] have shown that for semi-insulating dusts and fumes, which are composed primarily of inorganic oxides, silicates, and the like, the resistivity depends on temperature, humidity, and the presence or absence of so-called chemical conditioning substances or agents. The effect of temperature on fly-ash resistivity is usually of minor importance and is over-shadowed by the effects of humidity and the presence of natural conditioning substances. The general effect of humidity or water vapor in the gas is to lower the resistivity of dusts and fumes. Adsorption of condensed layers of water vapor on the particles is believed to be the basic physical mechanism involved. The condensed water films provide the electrical conductivity, and the effect may be greatly enhanced by the presence of very small quantities of certain chemicals. In general, we may picture the surface conductivity under these conditions as being similar to electrolytic conduction in liquids.

TABLE VI

Typical Field Values of Fly-Ash Resistivity.

Plant No.	Resistivity (ohm-cm.)
1	5×10^8
2	1×10^8
3	1×10^{10}
4	5×10^9
5	3×10^{10}
6	6×10^{10}

(10) White, H. J., "Characteristics and Fundamentals of the Back Corona Discharge," Presented at the Gas Discharge Conference, Brookhaven National Laboratory, October 27, 1948.

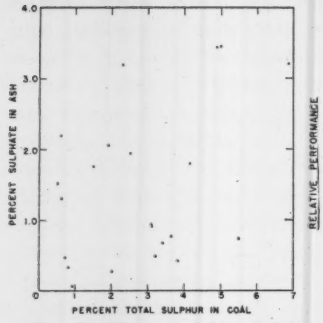

Fig. 5. Water-Soluble Sulphate Content of Ash versus Total Sulphur in Coal; 20 Representative Cases.

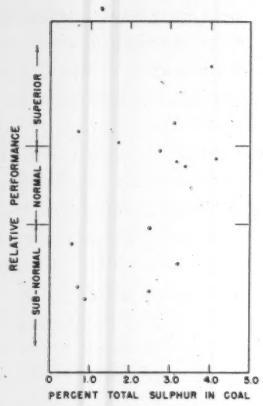

Fig. 6. Precipitator Performance versus Total Sulphur in Coal; 12 Representative Cases.

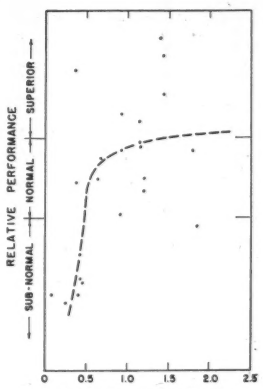

Fig. 7. Precipitator Performance versus Sulphate Content of Ash.

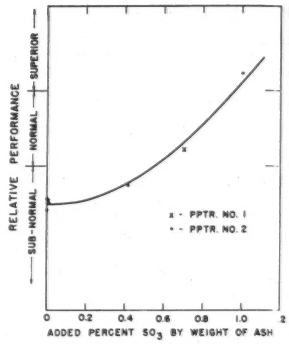

Fig. 8. Effect of SO_3 Conditioning in Improving Precipitator Performance.

The condensed water film on the ash increases with the amount of water vapor in the ambient gas, but decreases with increasing temperature. Thus the effect of humidity on resistivity will be greater at lower temperatures. In the case of boiler gases, the humidity normally is in the range of 5 to 10 % by volume. It is found by laboratory measurements that humidities of this degree will effectively lower the resistivity of most fly ashes by a factor of about 5 to 10 at temperatures of 250° to 300° F. At higher temperatures in the neighborhood of 400° F. or higher, the effect of moisture is small, while at temperatures of 200° F. or lower the effect may be very much greater. Thus the moisture content of boiler gases can influence resistivity to an appreciable degree, with the higher moistures being more favorable. Since moisture content of the gas is closely related to the volatile content of the coal, it follows that high-volatile coal in general will favor electrostatic collection.

Chemical compounds which in small quantities greatly reduce dust resistivity are designated "conditioning agents" and have been used in electrical precipitation for many years. Such compounds are specific for each type of dust, but the effective compound for any new type of dust can be found only by trial.

Research conducted in our laboratory during the past several years has disclosed and proved that SO_3 is the effective conditioning agent for fly ash.[11] It appears that the trace quantities of SO_3 naturally present in boiler gases are sufficient in most cases to maintain the resistivity of the ash below the critical value of 2×10^{10} ohm-cm. The troublesome higher-resistivity ashes occasionally encountered are the result of unusually low natural SO_3 content. Artificial addition of SO_3 to operating installations has substantiated laboratory findings on this point in that it is possible to improve electrical operation and substantially raise precipitator efficiency by the addition of very small percentages of SO_3 to the flue gas ahead of the precipitator.

Our research has indicated further that the electrical conductivity of the fly-ash particles is closely associated with the adsorption of SO_3 on the particle surfaces. This adsorbed SO_3 seems to be present as water-soluble sulphates, usually of the alkali earths (calcium, sodium, and potassium) or in some cases as sulphuric acid. It is occasionally found that the conditioning effect is determined primarily by the carbon or combustible content of the ash. These cases are rare, however, and for the vast majority of fly ashes the sulphate conditioning factor seems to be the predominant one.

Chemical analyses of coals by the Bureau of Mines and other agencies show that sulphur is present in at least a small degree in all coals. The amount present ranges from a small fraction of a percent up to about 5%. Under the high-temperature conditions existing in boiler furnaces, the sulphur is oxidized chiefly to SO_2 and to a small degree to SO_3. The actual concentrations found in furnace gases are of the order of magnitude of 0.1% for SO_2 and 0.001% for SO_3. These concentrations in any given case will depend on the sulphur content of the coal, and on furnace design and operating conditions.

Thus the sulphate adsorbed on the fly ash originates from the sulphur present in the coal. However, there is only a rough correlation between the amount of sulphur in coal and the amount of sulphate adsorbed on the fly ash. This is illustrated in Fig. 5, which is plotted from data obtained for a number of different boilers. The randomness of the points indicates the presence of other important factors.

These other factors are associated with furnace design and operation, and involve furnace temperatures, temperature gradients, and the possible presence of catalytic substances or conditions. We may conclude that both coal composition and furnace factors combine to determine the sulphate on the ash and therefore its electrical conductivity. Research is in progress on this whole problem,

(11) White, H. J., "Electrical Resistivity of Fly Ash," *Air Repair*, 3, 79 (1953).

but knowledge at present is limited because of the complicated nature of the phenomena and the difficulty of conducting controlled experiments.

Since the sulphur content of the coal influences the sulphate content of the ash, it is apparent that the ash resistivity and precipitator performance will also be affected by the sulphur present in the coal. Data on the relationship between percentage of sulphur in the coal and precipitator performance are plotted in Fig. 6 for a number of typical precipitator installations. Again, there is limited correlation, coupled with rather wide scattering of the points. There is no definite value of sulphur content which can be taken as a dividing point between good and poor performance. The general trend is for the higher-sulphur coals to give better performance, but reasonably good performance is possible even for coals having less than 1% sulphur.

In contrast to the rather low correlations shown in Figs. 5 and 6, our research studies have shown a high correlation between precipitator performance and sulphate content of the ash, illustrated in Fig. 7. There is clearly a critical zone in the region of 0.5% sulphate in the ash, below which precipitator performance is poor, and above which it is good. The scattering of the points in the region of good performance indicates the effect of other factors such as gas velocity, gas distribution, and rapping losses in determining over-all performance.

In summarizing this section, we may conclude that electrical resistivity is a fundamental factor in the electrostatic collection of fly ash. A critical value of resistivity of about 2×10^{10} ohm-cm. exists, below which precipitator performance will be normal and above which it will be increasingly subnormal. For the majority of fly ashes, the resistivity is governed primarily by the water-soluble or adsorbed-sulphate content of the ash. The critical value of sulphate content is about 0.5%. Lower values mean high ash resistivity, poor electrical operation, and relatively poor precipitator performance. Higher values in general are sufficient to insure good electrical operation and good precipitator performance. There is some correlation between sulphur content of the coal burned and precipitator performance, but no critical minimum value of sulphur content can be assigned. Good precipitator performance is possible even with coals having less than 1% sulphur. Much depends on furnace operation and firing conditions. Ashes having relatively high carbon contents of greater than about 15% usually will have low resistivity because of the conductivity of the carbon. These ashes generally give good electrical operation and precipitator performance, provided that grit loss is not excessive.

The dielectric strength of the collected ash on the plate electrodes is also an important electrical property of the ash. The flow of the corona current through the ash layers produces a voltage or potential drop across the layers in accordance with Ohm's law. When the resistivity of the ash is in the critical zone near 2×10^{10} ohm-cm., the voltage drop across the ash layer typically will amount to several kv. The existence of this voltage drop across the layer may be sufficient to cause it to break down electrically. When this happens, a spark flashes through the dust layer and is propagated to the discharge electrode. This is the source of the intensified sparking which occurs with dusts of excessive resistivity. Clearly, the higher the dielectric or breakdown strength of the dust layer, the higher the resistivity which may be tolerated for a given amount of corona current. Thus dusts of relatively high breakdown strength are less sensitive to resistivity effects than dusts of low dielectric strength.

For fly ash it is found that the dielectric strength of the bulk ash in layers of the order of ¼ in. to ½ in. thick ranges from values as low as a few hundred v./cm. up to as high as about 20 kv./cm., with an average figure in the range of 5 to 10 kv./cm. Ashes having very low breakdown strength usually are characterized by the presence of relatively high percentages or carbon, generally above about 10 to 15%. On the other hand, the presence of the carbon usually is sufficient to insure very low-resistance ash, so that the 2 effects nullify one another. Thus, in general the dielectric strength, although important, is of less significance than the resistivity.

Corrective Measures for High-Resistivity Ash

The amount of SO_3 which must be adsorbed on the fly-ash particles in order to provide adequate electrical conductivity usually corresponds to only a few percent of the sulphur present in the coal. There are no definitive studies of the factors or processes important in the formation of SO_3 in pulverized-coal-fired furnace gases. It is believed that the process is primarily one of conversion of SO_2 to SO_3 and that catalytic agents which are present naturally, play a major role. These catalytic agents may be the oxide-coated surfaces of the furnace, or the fly ash itself.

The conversion reaction is reversible and will occur only in that portion of the furnace in which the gas temperature is between about 800° and 400° C. This consideration leads to the expectation that boilers operating at low loads for which temperatures in general are lower and gas transit times are longer would be more efficient in the formation of SO_3. This expectation seems to be borne out by experience. Boilers which produce high-resistivity ash at high loads will as a rule produce lower-resistivity ash at lower loads, as shown by actual measurements on the ash.

In some cases it has been found that lowering gas temperature by only 20° F. to 30° F. (measured at air-heater outlet) is sufficient to substantially increase the SO_3 content of fly ash, with corresponding improvement in electrical operation and collection efficiency of the precipitator. These effects were observed with boiler load and coal held constant, the gas temperature being changed by adjustment of recirculation dampers by-passing the air heaters.

The artificial addition of SO_3 to boiler gases to improve precipitator operation with high-resistivity ashes has been tried both in the laboratory and in the field with successful results.[11] Tests were conducted on 2 separate field-precipitator installations which exhibited the clinical symptoms of high resistivity ash. In both cases precipitator performance was substantially improved by the addition of relatively small amounts of SO_3. This is illustrated in Fig. 8 in which precipitator performance is plotted in terms of the SO_3 added relative to the weight of the ash. The addition of 0.5 to 1.0% of SO_3 relative to the weight of the ash is sufficient to substantially improve the performance of the precipitators. It should be noted that the maximum amount of SO_3 added in these tests corresponds to only 10 to 20 ppm. of the flue gas by volume. Thus, exceedingly small percentages of SO_3 are effective. Although SO_3 conditioning has been proved effective for fly ash, and is in fact used quite extensively in certain smelter-precipitator applications, this solution to the high-resistivity-ash problem has not to date been used on a practical basis.

Experience has indicated that the high-resistivity ashes encountered in practice are usually in the borderline region just above the critical value of 2×10^{10} ohm-cm. The highest value we have ever measured in the field is 10^{11} ohm-cm. In this range of resistivity, precipitator operation tends to be subnormal, but still in the range where collection by electrostatic precipitators is practical. There are several measures related to the design and operation of the precipitator, particularly to the electrical energization, which are effective in improving performance. The effect of these borderline high-resistivity ashes is to produce intensified sparking and to limit the voltage and current which can be applied to the precipitator. When these conditions exist, it is of the greatest importance that the electrical operation be as stable and smooth as possible, so that the sparking will produce only minor disturbances. The clinical symptoms of unstable electrical operation are erratic and swinging readings on the meters and trip-outs of the rectifier sets.

Effective methods of improving the electrical stability include: use of half-wave voltage, adequate resistance in the primary circuit of the high-voltage transformer, elimination of high-voltage cables between the rectifier sets and the precipitator, and in some cases the use of appreciable amounts of high-tension resistance in the secondary circuit of the transformer. Half-wave voltage is especially effective because the relatively long time intervals between current pulses permit recovery from a spark within a period of less than one cycle, and therefore prevent the formation of high-current arcs. Primary resistance of at least several ohms is generally required to limit the severity of the sparks and to aid in rapid recovery of voltage after a spark. High-tension cables between the rectifier set and precipitator add unnecessary capacitance to the circuit, which prolongs and intensifies sparking and increases the tendency for the formation of high-current arcs. Secondary resistance is useful, especially where the other safeguards are not present or are inadequate.

Substantial increases in precipitator efficiency are possible through proper application of the foregoing measures. The improvement results from reducing the intensity of the sparks and permitting higher effective voltages and currents to be applied to the precipitator.

In some cases improvements in electrode rapping will improve electrical operation and precipitator efficiency and help counteract the adverse effects of high-resistivity ash. Improved gas distribution to the precipitator may also prove helpful. This not only provides more uniform loading of the precipitator, but also tends to insure more uniform electrical conditions, which in turn permits improved electrical operation. Increasing the sectionalization of the high-tension electrodes and using more electrical sets will frequently provide significant gains in collection efficiency. This is particularly true where these factors are minimal in the original design.

Precipitator Design

Basic precipitator design is governed by the fundamental precipitation equations (1) and (2) discussed in the preceding section. The collecting surface A required for any given application is given by equation (1), in which the gas flow rate V and the efficiency are specified by the application, while the precipitation rate w is determined from experience with similar precipitators.

In principle, w may be calculated from equation (2), but in practice, because of imperfect conditions and particle losses caused by re-entrainment and other factors not included in the idealized theory, it is necessary to use modified values of w derived from experience. The situation is similar to that existing in other fields of technology where theoretical equations are used with modified values of some of the constants to take account of departures from idealized conditions which can be only partially achieved in practice.

Since precipitator performance is closely related to fly-ash characteristics, it is clear that precipitator design must be based on either actual or assumed knowledge of these characteristics. In the case of existing boilers it is usually possible to determine the ash properties. For projected new boilers the ash properties can only be estimated, and unfortunately it is not usually possible to predict them with any degree of accuracy. The uncertainties arise chiefly from the great variability of coals and from variations in boiler characteristics and operating practices. In this situation, conservative design is indicated in order to provide a larger safety factor. However, economic pressures may prevent this, with the result that the seeds of unsatisfactory performance and disappointing results may be sown.

The 2 most important fly-ash properties which must be considered are particle-size distribution and electrical resistivity. A relatively coarse, gritty ash usually will be

more difficult to retain in the precipitator, and the design should incorporate methods for combatting this. On the other hand a very fine ash usually will require special attention to rapping.

Other fly-ash properties which should be considered in precipitator design include concentration and carbon content. The ash concentration (for a given gas flow) will determine the total amount of ash to be collected and disposed of, which in turn affects rapper requirements and hopper capacity. The carbon content may influence ash resistivity, the difficulty of retaining the ash in the precipitator, and also stratification of the suspended particles in the gas stream.

Precipitator design for high-resistivity-ash conditions should be conservative as to size, number of electrical sets, and rapping equipment. The electrical sets should be designed for maximum circuit stability in order to counter the adverse effects of precipitator sparking and to permit higher power input to the precipitator. Provisions should be made to ensure uniform and smooth gas flow and insofar as possible to avoid serious stratification effects. Automatic voltage control based on maintaining optimum sparking rate in the precipitator is also valuable as high-resistivity-ash conditions frequently are variable and intermittent.

Design Parameters

There are several basic precipitator-design factors which are useful for comparing designs and for predicting performance with given types of ash. These parameters include:

1. Specific collecting surface, $\frac{A}{V}$, defined as the effective collecting electrode surface per 1000 cfm. of gas treated. The effective collecting surface is considered to be the total equivalent plane area of the plates exposed to the corona discharge. The details of the plate structure are not considered in calculating this area, only the over-all width and length. High-efficiency fly-ash precipitators in the range of 95 to 98% usually are designed with specific collecting surfaces of the order of 100 to 200 ft.^{2}/1000 cfm. of gas. Precipitator size for a given gas flow is basically determined by this parameter, with the larger values being the more conservative.
2. Duct width, which is defined as the distance between the surfaces of adjacent collecting electrodes. The electrode thickness is excluded in determining duct width. For example, perforated-plate electrodes of the type commonly used in fly-ash service are ¾ in. thick and are spaced 8¾ in., center-to-center. The duct width is then 8 inches or (the actual open width between adjacent plates).
3. Precipitator gas velocity, v, defined as the average gas velocity in the precipitation zones. The cross-sectional area for gas flow is based on the actual duct widths and does not include the thickness of the plate electrodes, which may amount to as much as 20 or 25% of the total in some cases, as, for example, with V-plates which are 2 in. thick.
4. Treatment time, t, defined as the calculated average time the gas is in the precipitation zones of the precipitator. Treatment time is sometimes used as a basis for comparing precipitation capacity for different designs, but is less fundamental than the specific collecting surface. If L is the total treatment length in the direction of gas flow (sum of plate widths), then $t = L/v$. Note that this definition of treatment time is physically sound. Other methods of calculating treatment time, such as, for example, using the over-all dimensions of the precipitator shell, give larger but fictitious values. For some designs treatment times calculated by the latter method will be almost twice as large as those calculated from the physically sound method.
5. Specific electrical energization $\frac{P}{V}$, defined as the useful power output rating of the rectifier sets per 1000 cfm. of gas treated. For example, if 6 rectifier sets, each rated for 7500 w. output, are used with a precipitator treating 450,000 cfm., the specific electrical energization would be

$$\frac{P}{V} = \frac{6 \times 7500}{450} = 100 \text{ w./1000 cfm.}$$

Since high-voltage rectifier sets vary markedly in electrical efficiency, depending on the type and design, neither the kva. rating of the transformer nor the power input should be used in making comparisons. For example, mechanical rectifier sets of the type which have been used in precipitation service for many years have an efficiency of about 30% on fly-ash precipitators and use a 25-kva. transformer. In contrast, recently developed tube rectifier sets for the same service have an efficiency of about 50% and use a 15-kva. transformer. However, the useful power output is the same for both sets (7.5 kw.) so that they are equivalent as far as precipitation effect is concerned. Superficial comparisons made on the basis of kva. ratings of the transformers would heavily penalize the tube set, but such a comparison would be false and misleading. For example, in actual practice 3 of the 15-kva. tube sets would be capable of supplying 22.5 kw. to a precipitator, while 2 of the 25-kva. mechanical rectifier sets could supply only 15 kw. even though the total kva. ratings of the mechanical rectifier sets is the larger.

The specific electrical energization used for high-efficiency fly-ash precipitators is generally of the order of 75 to 1500 w./1000 cfm. of gas, with the higher figures being the more conservative.

Combination Inertial and Electrostatic Collectors

Combination inertial and electrostatic gas-cleaning systems have been used for over 30 years in a number of

fields, but their application to fly-ash collection dates only from about 1946. A variety of types of inertial collectors have been used for this service including skimmer-type cyclones, small-diameter centrifugal collectors, and several cone and louver types. Collection efficiency for inertial separators is closely related to draft loss and to the particle-size distribution of the ash. In general, efficiency increases with increasing draft loss and with coarser ash. Draft losses range from about 1 in. up to 3 or 4 in., water gauge.

Combination collectors may be arranged with the inertial unit either fore or aft, but in certain applications one arrangement may be preferred over the other. The preference depends primarily on the ash treated. For example, with a coarse, gritty ash it is usually advantageous to place the inertial unit ahead of the precipitator. This arrangement permits the precipitator to treat a finer, more homogeneous ash with resultant better over-all performance. On the other hand, with a fine ash the inertial unit, if used at all, may better be located following the precipitator. This eases the precipitator rapping problem, and in some cases where carbon contributes to ash conductivity, will provide a lower-resistivity ash for the precipitator than would be obtained if the inertial unit preceded it.

The operating power for inertial collectors is supplied indirectly by the station's fans, and appears in the form of draft loss across the collectors. Elementary thermodynamic principles show that the power consumed is given by equation (3):

$$P = 0.118\ V\Delta p \qquad (3)$$

where P = operating power in kw.
V = gas flow in units of 1000 cfm., and
Δp = draft loss in inches of water

When losses in the fans and driving motors are included, the power is increased to about

$$P = 0.175\ V\Delta p \qquad (4)$$

or 0.175 kw./1000 cfm./in. of draft loss.

Typical collection efficiencies for inertial separators as determined from tests on combination collectors in fly-ash service are given in Table VII. The efficiencies range between about 50 and 80%, with an average of 70 to 75%.

It is well known that the efficiency of inertial separators increases with particle size and with particle density. Data on this relationship for certain types of collectors may be found in the literature.[12] Inertial-collector performance guarantees are commonly based on particle size. However this is rather vague, since there is no standard or even generally accepted method for determining particle size. Further, in the case of projected new boiler installations, the particle-size distribution cannot be predicted with much accuracy. Hence, it is safer and frequently more realistic to base the anticipated performance of inertial collectors on experience in similar installations.

The choice between electrostatic precipitators alone, and combination inertial-electrostatic collectors for fly-ash removal is by no means simple and does not appear to have a categorical answer. Rather, the decision should be based on careful technical and economic analysis of each proposed installation. The properties of the fly ash to be collected will play a major role in the analysis. In general, coarse, gritty ashes will favor the use of combination collectors, while relatively fine ashes will favor the precipitator alone. A good example of the latter case is the ash produced by cyclone-type furnaces, which typically runs 85% less than 10 μ.

The most important technical arguments which have been advanced in favor of combination collectors are: (1) combination units provide complementary large- and fine-particle collection characteristics; (2) their efficiency characteristics with variable gas flow are also complementary and more uniform; (3) improved gas flow distribution to the precipitator is obtained with some types of close-coupled inertial collectors used ahead of the precipitator; and (4) in the event of failure of some of the precipitator sections, there will always be some collection with the inertial collector. However, this last point is of limited validity because of the high reliability of modern, well-designed, sectionalized precipitators and the fact that inertial collectors are also subject to trouble.

Arguments cited against the use of combination collectors include: (1) inertial collectors inherently have

(Concluded on page 62)

TABLE VII
Inertial Collector Performance.[a]

Plant No.	Collector Type	Draft Loss Inches H_2O	Particle Size $+44\mu$	Gas Flow cfm.	Efficiency %
1	Multi-cyclone, 9-in.-dia. tubes	2.4	21%	160,000	77
2	Wedge type, low-draft loss.	~0.5	49	110,000	47
3	Multi-cyclone, 9-in.-dia. tubes.	3.5-4.1	2	110,000	68
4	Cyclone, 42-in.-dia. tubes.	3.5	...	190,000	66
5	Slotted cone.	~1.5	26	420,000	70-80
6	Multi-cyclone, 9-in.-dia. tubes.	1.8	30	70,000	82
7	Skimmer type, 9-in.-dia. tubes.	~2.5	2	219,000	72
8	Multi-cyclone, 3 in.-dia.-tubes	1.4	13	234,000	65

(a) These figures are for combination inertial-electrostatic collectors, with the inertial collector preceding the precipitator in all cases.

The Mechanism of Separation in the Louver-Type Dust Separator*

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Georgia Institute of Technology
Atlanta, Georgia

The louver dust separator (Fig. 1) is an inertial-type separator. It is characterized by a stream of dust-laden air incident upon a row of blades or vanes which form the louver face. The larger portion of the air stream, clean air, turns and passes through the blades and the smaller portion of the air stream, blowdown, continues in its original direction without passing through the louver face. The blades are so arranged that the dust because of its high inertia is unable to pass through the blades and is concentrated in the blowdown air stream.

The louver separator has been manufactured and used for some time; yet, very little has been known of the mechanism by which it separates dust particles from a gas stream. The prior extent of understanding is best expressed by the statement that it is easier for air to negotiate a sharp turn than it is for high-inertia dust particles.

Harwell[1] and Matheson[2] presented analyses of performance data for a louver separator; neither of the two analyses provided an understanding of the separation process. A literature search by Matheson[2] showed that there is very little in the literature that is helpful in understanding the mechanism of separation.

This investigation has had as its first object an understanding of the process of separation. This involves a knowledge of why the particles that are separated are not able to pass through the louver blades and of how some particles manage to escape separation. The second object of the investigation was to use this knowledge of the separation mechanism to design a separator with improved performance. The redesigned separator was to embody features which would maximize the forces and effects causing particle separation and minimize those causing particles to pass between the blades.

(1) Harwell, C. W., "An Initial Study of a Louver-Type Dust Separator," M. S. Thesis, Georgia Institute of Technology, School of Mechanical Engineering, 1950.

(2) Matheson, C. M., "A Two-Dimensional Study of a Louver-Type Dust Separator, M. S. Thesis, Georgia Institute of Technology, School of Mechanical Engineering, 1952.

*Presented at the Annual Meeting of The American Society of Mechanical Engineers, New York, N. Y., November 28 to December 3, 1954.

Preliminary Studies

Method of Investigation

The investigation was conducted in 2 parts. For the preliminary studies the apparatus of Matheson[2] was modified and used to study the mechanism of separation. The second part of the investigation consisted of the design and construction of a new separator as well as an analysis of its performance.

Almost all that was learned in this investigation was the result of being able to follow the paths of the particles as they passed through the separator. The particle paths were made visible by a system (Fig. 1) developed during the study. This system was suggested by the Tindall meter[3] and uses the same principle. A very intense beam of light is focused on the particles, the beam of light being perpendicular to the direction of the particle motion. The paths of the particles in the plane formed by the light beam and the particle motion are then visible, provided the background is completely dark.

Matheson's apparatus was modified (Fig. 1) so that this system could be used to follow the particle paths. A ½-in. x 8-in. glass window was fitted into the front wall of Matheson's separator to admit the light beam. The

(3) DallaValle, J. M., "Micromeritics," 2nd Edition, Pitman Publishing Corporation, New York, N. Y., 1948, p. 201.

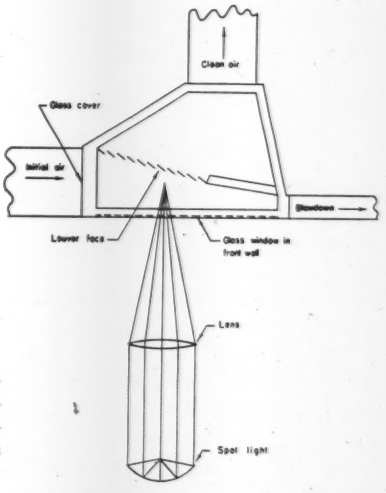

Fig. 1. Two-Dimensional Louver Separator with Modifications for Particle-Path Observations.

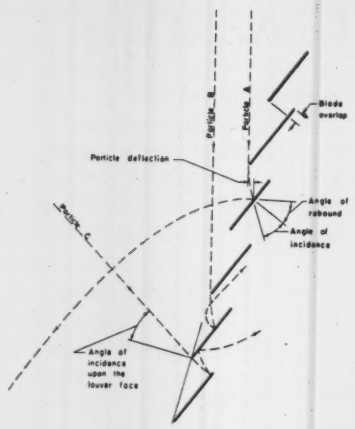

Fig. 2. Sketch of Representative Particle Paths in Straight-Blade Separator.

bottom, all interior walls, and the louver blades were painted flat black to serve as a dark background for the illuminated particles and to keep down reflected light. A standard photographic reflector spot bulb was used as a light source. A lens (8-in. focal length approximately) was used to focus the light on the particles. With this arrangement the particles could be seen as thin threads of light as they passed through the high-intensity beam. Although this arrangement illuminated only about ½-in. band through the separator, the entire pattern of particle paths could be determined by moving the beam to all parts of the separator.

Evaluation of Performance of Matheson's Separator

Immediately upon observing the paths of the particles in the separator it was evident that in the past the importance of the effects of particle inertia and of particle impacts with the louver blades had been underestimated. In fact, a number of the larger particles would strike the louver face and rebound with a high enough momentum to cause them to cross the air stream and strike the front wall of the separator.

By studying the particle paths it was seen that the separating effect of the blade shape used by Matheson was almost entirely dependent upon the momentum of the particle after an impact. To understand how the blade separates, examine the path of a representative particle (particle A Fig. 2). Particle A enters the separator in a straight-line path in the direction of the incoming air stream. No particles could be observed that did not enter the separator along such a straight-line path. Let particle A be a particle that just misses the tip of a blade so that particle A will penetrate well into the opening between the blades before impact and hence will be a difficult particle to separate. As particle A approaches the louver face there is no observable deviation from its straight-line path until it passes close to the tip of a blade. After the particle just misses the tip of the blade it begins to be deflected by the drag of the air passing between the blades.

Fig. 3 shows a sketch of the streamlines near the louver blades. The drag deflects the particle only about 5° before the particle collides with the blade surface. Particle A makes a "good" impact with the blade surface. A "good" impact is an impact such that the angle of rebound is approximately equal to the angle of incidence and such that there is only an average linear momentum loss. After the impact, particle A rebounds back into the air stream that is passing between the blades. The momentum of the particle is sufficient to overcome the drag between the blades, and the particle passes back out into the air stream down the louver face. Down the louver face is the direction from the inlet toward the blowdown parallel to the front wall. The speed of the particle away from the louver face decreases and the speed down the face increases because of the drag of the air stream down the louver face. The particle A may move 6 to 8 in. down the louver face before the effect of the impact is no longer appreciable.

The pattern of the streamlines near the louver blades (Fig. 3) was estimated by observing the behavior of very fine particles as they passed through the separator. These particles were all below 1 μ in diameter. The location of the air stagnation point on a blade was determined by the presence of a sharp-pointed buildup of fine dust. The buildups were obviously at the stagnation point because they were fragile and fell off if the blade was tapped lightly.

The limit of the particle deflection before impact with the blade surface could be observed other than by particle paths. The blade face became brightly polished by the particle impacts. The end of the polished area of the blade was distinct and indicated the limit of particle deflection.

Particles were observed to pass between the blades because of "bad" impacts and because of too small an angle of incidence upon the louver face. A "bad" impact, used in contrast to a "good" impact, is an impact which is more inelastic than a "good" impact and which has an angle of rebound quite different from the angle of incidence. The "bad" impacts can be attributed to the irregular shape of the dust particles.

Particle B (Fig. 2) is a representative particle which makes a "bad" impact. Particle B enters the separator and proceeds to the point of impact as did particle A. However, the particle makes a "bad" impact and rebounds with a greatly reduced momentum and with an unfavorable angle of rebound. As the particle passes back into the air stream between the blades it does not have enough momentum to overcome the drag and it is carried between the blades.

Some particles were observed to pass between the blades because of too small an angle of incidence upon the louver face. Particle C (Fig. 2) is an example of a particle that is incident upon the louver face with too small an angle for separation. Particle C is incident upon the blade surface in such a manner that after impact there is

no tendency for it to pass out from between the blades. The drag of the air stream passing between the blades then carries the particle through the louver face.

Performance of Louver

A study of the over-all performance of the louver showed that the blades near the blowdown or downstream end of the louver did not perform as well as the blades near the inlet, an inherent weakness of this type of separator. As the air stream moves toward the blowdown the dust concentration becomes higher; thus, the downstream blades have more particles incident upon them than do the upstream blades. Accordingly the last blades, which have the largest number of particles to separate, are the blades through which the largest number of particles pass.

There were a number of features of Matheson's apparatus that tended to amplify the nonuniform blade performance. The first and most important was a nonuniform air velocity through the louver face. The highest velocity was between the last few blades. Because of this high velocity, the performance of the blades near the blowdown was decreased. The high velocity between the blades is detrimental to performance because the higher the velocity between the blades the greater the drag tending to carry the particles through the louver. Thus, the nonuniform flow through the louver face decreased the performance of the louver blades where good performance was most needed. The nonuniform air flow was caused by the shape of the louver housing both in front of and in the rear of the louver face. The wall in the rear of the louver was so placed that it obstructed the flow through the upstream blades more than that through the downstream blades. The inlet cross-sectional area of Matheson's apparatus was 6 in.^{2}, and the blowdown cross-sectional area was 2 in.^{2} Hence for blowdowns of less than 30% there would be a lower velocity and higher pressure in the blowdown duct than in the inlet duct. This higher pressure in the blowdown section of the separator caused a higher pressure in front of the blades near the blowdown end of the separator than in front of the blades near the inlet. Thus, more air was forced through the last blades of the separator.

When the blowdown air flow was about 5%, the air stream in the blowdown end of the separator was found to bend gradually before passing between the blades. The bending air stream caused the particle paths to bend toward the louver face. As the particles bend toward the louver face, the angles of incidence upon the louver face become smaller and the particles have much less chance of being separated.

When the blowdown air flow was less than 5%, an eddy filled the space in front of the louver face just upstream from the blowdown outlet. This eddy completely destroyed the orderly motion of the particles in front of the downstream part of the louver face. With particles traveling in random paths, a large number of the particles were incident upon the louver face in a manner such that separation was impossible.

The effectiveness of the downstream blades was also

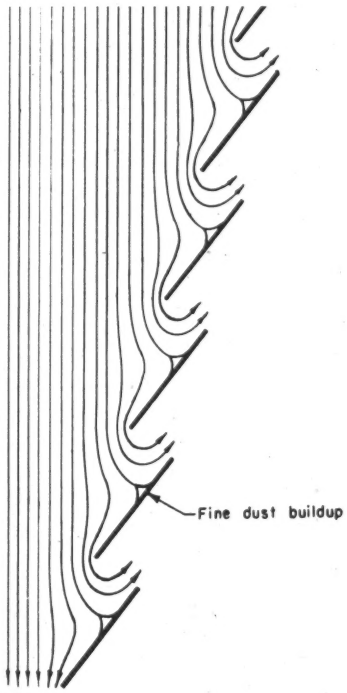

Fig. 3. Sketch of Streamlines near Straight Louver Blades.

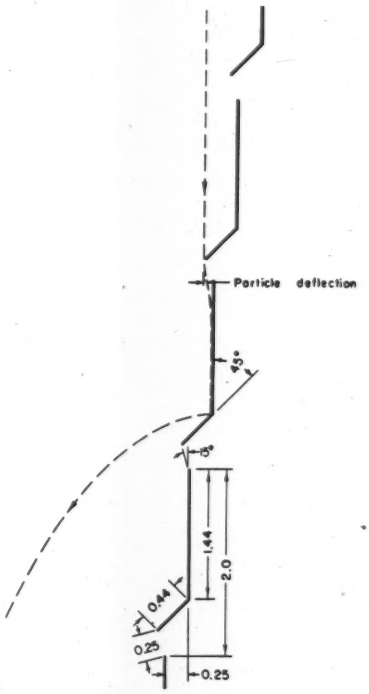

Fig. 4. Blade Design and Sketch of Typical Particles Path.

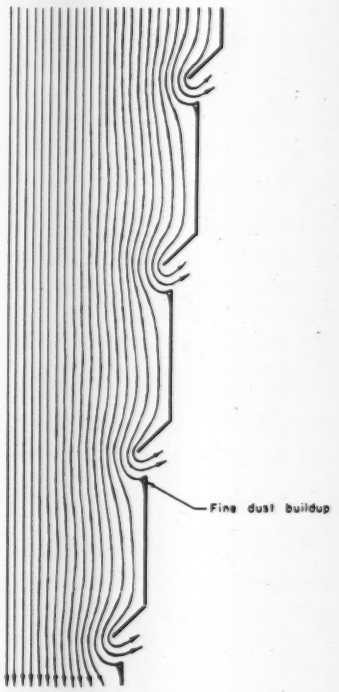

Fig. 5. Sketch of Streamlines near Louver Blades.

decreased by particle rebounds from the front wall of the separator. This front-wall effect became more pronounced the shorter the distance between the louver face and the front wall. This effect is best explained by following a representative particle. A particle impacts a blade surface in the usual way and rebounds after a "good" impact. The particle rebounds with enough momentum directed across the air stream to carry it to the front wall. The particle impacts the front wall with a "good" impact and rebounds across the air stream again. The particle then is incident upon the louver face with an angle which makes separation difficult. All of the particles that were participating in this effect were large high inertia particles.

Conclusions from Preliminary Studies

The first conclusion was that any overlap (see Fig. 2) of the straight blades was unnecessary. Any particle that impacts the blade surface behind the point of zero overlap will rebound with a momentum directed through the louver face, and hence cannot be separated. Therefore, any overlapping portion of the blades does not aid separation but only restricts the flow of air between the blades.

The flat blade design does not develop the full capabilities of the louver separator. The blade design was poor in that the particles experienced the drag between the blades once before impact with the blade surface and again after impact. The drag after impact was especially bad because on impact the particles lose much of their momentum, and therefore, after impact their motion is strongly influenced by the drag. The drag after a "bad" impact was strong enough to carry the particles between the blades. Thus, if the particles do not have sufficient momentum away from the louver face after impact they will pass through the louver.

The shape of the housing around the louver is of paramount importance. For good separator performance the housing must be so shaped that there will be the same air flow through each opening in the louver or possibly a decrease in air flow through the openings with distance down the louver face. In any case, there should not be an increase in flow through the openings with distance down the louver face. In order to achieve this uniform flow through the louver face the velocity of the air stream in front of the louver face must be maintained constant from inlet to blowdown. The back wall and clean-air outlet of the separator must be arranged so that they will maintain a uniform back pressure on the louver.

Separator Design

Blade Design

To minimize the weaknesses of the flat blade design, an effort was made to separate the region where the particles impact the blade from the opening between the blades. A more effective blade design would cause the particles to rebound into an air stream directed down the louver face and not between the blades. In this way, if a particle made a "bad" impact it would not pass between the blades. This amounts to separating the action of the blade into 2 operations. First, because of impacts and resulting rebounds, the particles are moved across the air stream and away from the louver face. The second operation is to allow the air to pass between the blades without allowing any particles to pass. Apparently the second operation is all that is necessary to separate the particles. However, if the particles were not moved away from the louver face a very concentrated dust band would develop in front of the louver face and a particle after first approaching the louver face would pass very close to all remaining openings between the blades. Hence, the number of opportunities for a particle to pass through the louver face would be increased.

Several blade designs were mounted in the apparatus diagrammed in Fig. 1 and observed in operation. The blade shape which appeared to have the best performance is shown in Fig. 4. To understand the operation of this blade design, examine the path of a representative particle. The particle enters the separator along a straight-line path in the direction of the inlet air stream. The particle is one that just misses the front tip of a blade. The particle does not deviate observably from its straight-line path until after it passes the tip of the blade which it just misses. After the particle passes the front tip of the blade, it passes into the air stream that is directed between the blades. The drag on the particle deflects the path, but the particle continues by virtue of its own inertia until it completely crosses the stream passing between the blades. The particle then passes into the air that is flowing down the straight portion of the blade. As the particle approaches the inclined portion of the blade it feels the effect of the air stream that has curved out along the inclined portion of the blade. The particle, affected only slightly by drag from this air stream, continues and impacts the inclined portion of the blade. The particle rebounds back into the air stream that has curved out the inclined portion of the blade and then out into the main air stream down the louver face. The velocity of the particle away from the louver face decreases and the velocity down the face increases because of the drag of the main air stream. The particle may travel 6 to 8 in. after the impact before the effects of the impact are no longer observable.

The streamline pattern near the louver blades is

Fig. 6. Photograph of Pattern Eroded into Glass Top of Separator.

sketched in Fig. 5. As before, the stagnation points were determined by the location of fine dust buildups.

Fig. 6 shows the pattern of the particle paths after impact with the inclined portion of the blades. The figure was obtained by photographing the pattern eroded into the glass top of the separator.

If the particle should make a "bad" impact with the inclined surface of the blade, it will not pass through the louver face but will rebound with small momentum into the air stream along the inclined portion of the blade. As a result of the "bad" impact the particle will be carried only a small distance away from the louver face. Particles which are deflected more than the average particle as they pass in front of the blade opening will impact the straight portion of the blade. After the impact, such a particle will rebound into the air stream flowing down the straight portion of the blade. This air stream carries the particle to a second impact with the inclined portion of the blade. With enough deflection a particle could pass directly between the blades without an impact. No particles were observed that were deflected to this extent.

The Louver-Housing Design

A louver housing was designed which would as nearly as possible give the same velocity between each of the louver blades, and which would as nearly as possible keep the velocity of the main air stream down the louver face constant from inlet to blowdown. In order to explain the design of the louver housing, it is necessary to define the variables which were the basis for its design. Inlet area is the cross-sectional area of the inlet to the separator. Blowdown area is the cross-sectional area of the passage in front of the end of the last blade in the louver. The frontal area of the louver face is the projected area of the louver face on a plane normal to the direction of the inlet-air stream. The open area of the louver face is the sum of the areas of all the openings through the face. The areas of the openings are measured in a plane that will give the maximum area. The frontal area of a blade is the portion of the frontal area of the louver that is the contribution of the blade. The open area of a blade is the area of the opening after the blade. The design velocity between the blades is the inlet velocity times the ratio of the blade frontal area to the blade open area. Thus, if a louver of constant ratio of blade frontal area to blade open area is operating at the design velocity between the blades, the air velocity through the louver face is constant.

The blades shown in Fig. 4 are designed so that the ratio of blade frontal area to blade open area is 1 for each blade. The object of the louver-housing design was to keep the velocity of the air stream down the louver face constant from inlet to blowdown. This requires, first, that the blowdown area must be selected to correspond to the blowdown flow desired. For example, if a blowdown flow of 5% is desired, the blowdown area must be 5% of the inlet area. The blowdown area must be located so that the blowdown portion of the inlet-air stream can proceed

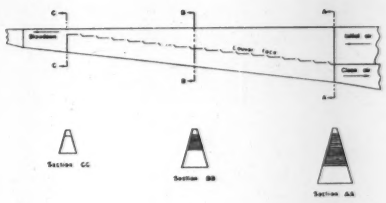

Fig. 7. Simplified Sketch of Separator.

to the blowdown without changing direction. If a louver of constant ratio of blade frontal area to blade open area is to operate at the design velocity between the blades, the frontal area of the louver and the blowdown area must project and together form an area coincident with the inlet area. Otherwise, the air stream down the louver face will change direction and speed before passing between the louver blades. Changes in direction or speed of the air stream down the louver face will cause a nonuniform pressure in front of the louver face. Such a pressure condition does not permit the same flow through each of the louver openings.

There are a number of designs for louver housings that fulfill the requirements for keeping the velocity of the air stream down the louver face constant. The 2-dimensional separator satisfies the requirements, but if it is desired to design for small blowdown flows the louver face must be very close to the front wall near the blowdown. This is undesirable because the front-wall effect will be increased.

The conical separator with the louver face formed into the frustrum of a right circular cone fulfills the requirements for uniform air velocity down the louver face. In this design there is no front wall, but the front-wall effect is still present. In the conical separator, the dust particles will, after impact, cross the separator and impact the louver face diametrically opposite the initial impact. If the diameter of the cone is small enough and the particle momentum after impact high enough, the second impact will be at angle of incidence upon the louver face such that separation will be difficult, if not impossible. The conical separator has the advantage that the length of the blades decreases with distance down the face. Fewer particles are incident upon the shorter blades; hence, the shorter blades tend to compensate for the larger number of particles that pass through a unit length of opening between the last blades.

A sector of a conical separator fulfills the requirements for uniform air velocity down the louver face and has the advantages of a conical separator.

Housing for Test Separator

The housing for the test separator was designed to approximate a 30° sector of a conical separator. Actually the cross section of the separator was an isosceles trapezoid rather than a circular sector. The separator was designed to be a sector of a complete separator to facilitate particle-path studies, and so that the approximate characteristics of a large separator could be determined with a small

Fig. 8. Photograph of Separator.

blower and other test equipment. The separator was constructed with a trapezoidal cross section rather than a circular sector to facilitate fabrication.

The inlet area of the separator was 9.53 in.^{2}, and the blowdown area was 0.573 in.^{2} Thus the design blowdown for the separator was 6.01%. Simplified sketches of the separator are given in Fig. 7. A photograph of the separator is given in Fig. 8.

The outlet of the separator was placed at the upstream end of the louver so that the clean air makes a 180° turn in passing through the separator. The outlet was placed so that the low velocity and high back pressure would be in the rear of the last blades of the louver. This was to keep the flow between the last blades of the louver equal to or smaller than the flow through the upstream blades and thereby compensate for the inherent poor performance of the last blades. Thus, the blowdown portion of the initial air stream passes down the front of the separator without changing speed or direction. The clean air continues in the direction of the inlet-air stream without changing velocity until it reaches the louver face. On reaching the louver face, the clean air makes a 180° turn in passing through the louver and then passes behind the louver to the outlet.

A detailed cross section showing the constructional features of the separator is given in Fig. 9. The top of the separator was plate glass, and glass windows were placed in the front wall so that the particle paths could be ob-

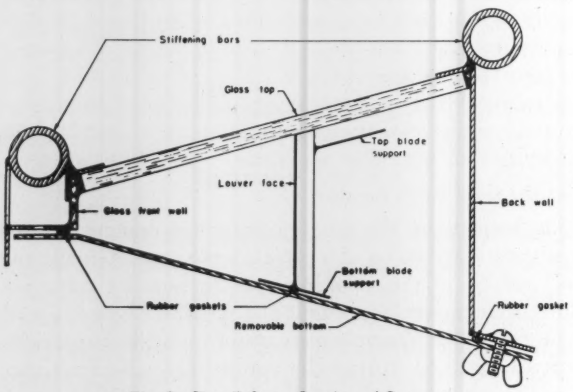

Fig. 9. Detail Cross Section of Separator.

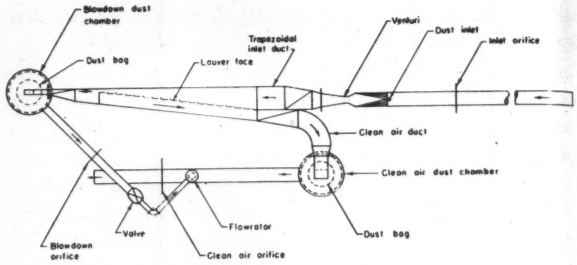

Fig. 10. Sketch of Apparatus for Separator Test.

served. The bottom of the separator was held in place with screws and wing nuts so that it could be removed for changes in the separator-blade assembly. One-half in. pipe stiffening bars were welded to the separator to give it rigidity. The housing was fabricated of 18-gage sheet steel by welding. The louver was a soldered assembly of 28-gage galvanized sheet steel.

Apparatus

The Air System

Figs. 10 and 11 show the layout of the equipment. The air for the tests was supplied by a motor driven Sturtevant 7-stage blower. The supply air, metered through a thin-plate orifice, passed into a 15-in. length of standard 3-in. pipe. At this point the dust was fed into the air stream. The 3-in. pipe was changed through a transition section to the 2-in. x 3-in. rectangular entrance to a venturi section. The venturi was employed to insure thorough mixing of the dust into the air stream. The 2-in. x 4-in. outlet of the venturi was changed by a transition section to the trapezoidal inlet cross section. Six in. of trapezoidal duct were provided in front of the inlet to the separator.

The clean air stream which made a 180° change of direction in passing through the separator passes from the separator through the trapezoidal outlet. The outlet cross section was changed by a transition section to a 2-in. x 4-in. rectangular duct. The air stream made a 90° turn in the horizontal plane, passed through a transition to a 2-in. x 3-in. duct, and made a 90° turn in the vertical

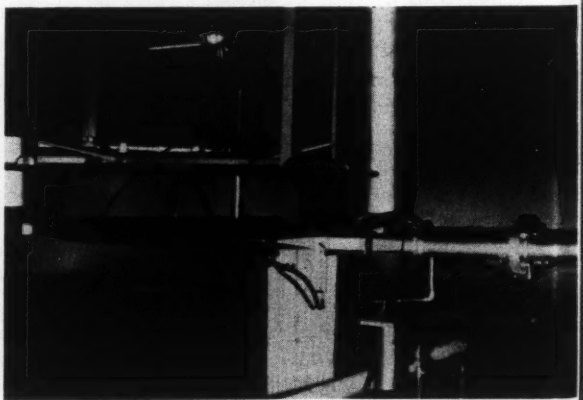

Fig. 11. Photograph of Apparatus for Separator Test.

plane before entering the dust-collecting chamber. For the outlet from the dust chamber, a length of standard 3-in. pipe provided with an orifice meter was fitted into the side of the dust chamber at the bottom.

The blowdown air stream which flowed from the separator through a trapezoidal outlet passed through a transition to a 1-in. x 2-in. rectangular duct. The blowdown stream made a 90° turn in the vertical plane and passed into the blowdown dust-collecting chamber. The outlet from the blowdown dust chamber was a length of 1½-in. standard pipe fitted with a metering orifice. For small blowdown flows a calibrated flowrator was attached to the outlet pipe.

The air flows were regulated by obstructing the blower inlet, by adjusting a globe valve in the outlet from the blowdown dust chamber, and by varying an obstruction in the inlet to the clean-air dust chamber.

Dust-Collection Chambers and Dust Bags

The dust-collection chambers were cylindrical cans with flanged tops. The covers were connected to the ducts coming to the chambers and were secured to the flange by means of screws and wing nuts. The dust-collecting bags were Electrolux cleaner bags. The clean-air bag was made from 4 Electrolux bags sewed end to end and the blowdown bag was a single bag. The bags were sealed in place by clamping the flanged metal and rubber mouth of the bag between the flange on the top of the collecting can and the cover for the can. The wing nuts and screws provided the pressure for the seal and made disassembly for weighing easy. The outlets from the chambers were fastened into the sides near the bottom.

Dust Feed

A dust feeder (Fig. 12) with a wide range of rates of feed was designed and built. The rate of feed ranged from 2.72 gm./min. to 255 gm./min. The feeder was essentially a hopper closed at the bottom by a vibrating trough. The rate of feed was varied by adjusting the opening between the bottom of the hopper and the trough. The dust from the trough fell into a second hopper which opened at the bottom into an air injector. The injector, operated by compressed air, picked up the dust from the trough and some air from the room and injected them into the air stream entering the separator.

Discussion of Results

Twenty runs were made. Runs 1 through 10 were to determine the effect of the blowdown flow on dust separation. Runs 11 through 15 were to determine the effect of initial dust concentration on dust separation. Runs 16 through 20 were to determine the effect of initial air velocity on dust separation and pressure drop through the separator. Detailed test procedure and recorded data are contained in a thesis by one of the authors.[9]

Effect of Blowdown

The effect of blowdown air flow on dust separation is shown in Fig. 13. The point at which the performance of the separator breaks and decreases sharply is significant. This point is at about 6% blowdown, which is the blowdown for uniform velocity down the louver face. Thus, as would have been predicted from the particle-path studies, the performance of the separator is decreased if the velocity of the air stream decreases as it passes down the louver face.

It is interesting to examine Matheson's plot of the variation of dust separation with blowdown.[4] Matheson's apparatus when set for 22.5° face angle would have operated with a uniform velocity down the louver face at a blowdown of about 30%. Matheson's extrapolated performance curve breaks at a blowdown of about 30% as would be predicted. Thus, it is concluded that the per-

(4) Matheson, C. M., "A Two-Dimensional Study of a Louver-Type Dust Separator M.S. Thesis, Georgia Institute of Technology, School of Mechanical Engineering, 1952, p. 54.

(9) Smith, J. L., "The Mechanism of Separation in the Louver-Type Dust Separator," M. S. Thesis, Georgia Institute of Technology, School of Mechanical Engineering, 1953.

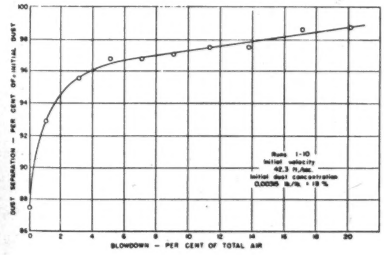

Fig. 13. Effect of Blowdown on Dust Separation.

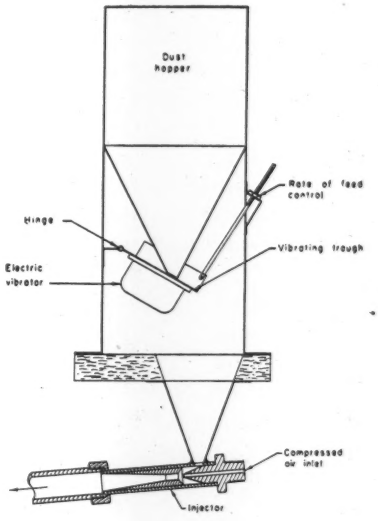

Fig. 12. Sketch of Dust Feeder.

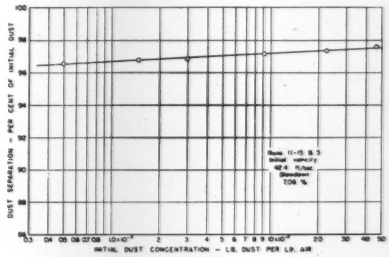

Fig. 14. Effect of Initial Dust Concentration on Dust Separation.

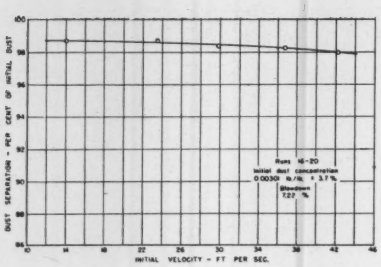

Fig. 15. Effect of Initial Air Velocity on Dust Separation.

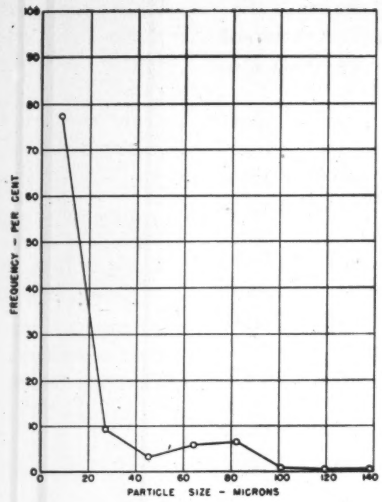

Fig. 17. Particle-Size Distribution of Initial Dust.

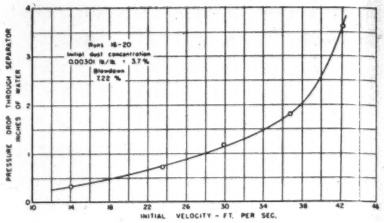

Fig. 16. Effect of Initial Air Velocity on Pressure Drop through Separator.

formance of the louver separator is decreased sharply if the ratio of blowdown air flow to total air flow is much less than the ratio of blowdown area to inlet area.

Effect of Initial Dust Concentration

The effect of initial dust concentration on dust separation is shown in Fig. 14. The results show that the per cent of the dust that is separated is almost independent of the initial dust concentration. This is in agreement with Harwell.[5] The trend is to a slightly increased separation with increasing initial concentrations. This is probably due to collisions between the particles in the air stream.

Effect of Initial Air Velocity

The effect of initial air velocity on dust separation is given in Fig. 15. This part of the test showed that to a large extent the performance of the separator is independent of the initial air velocity. The trend was to a slightly increased performance with decreased initial air velocities. In Matheson's test the trend was to improved performance at higher velocities. The fact that the performance is independent of initial air velocity is important in view of the variation of the pressure drop through the separator with initial air velocity.

Fig. 16 shows that the pressure drop through the separator increases rapidly with increasing initial air velocity. Thus, at low initial air velocities, the separator will separate the dust without absorbing the power that it would at high velocities.

It is felt that the range of initial air velocities tested covers the range that is important. Higher velocities than those tested are impractical because of the high pressure drop through the apparatus. Velocities lower than those tested would not transport the large dust particles.

The particle-path observations also showed that the initial air velocity did not have a marked effect on the particle paths.

Particle-Size Distribution

The dust that was used throughout the tests was the Norton Company's Alundum abrasive with a manufacturer's grain-size classification of 240. This abrasive is aluminum oxide which has a specific gravity of about 4.

Five dust samples were studied. The first was a sample of the input dust. The second and third samples were from the clean air bag and the blowdown bag with the separator operating at a low initial air velocity, and the last 2 samples were with the separator operating at a high initial air velocity.

The particle sizes were determined by the standard method for determining particle sizes by microscopic measurements[6]. The size of 200 particles in each sample was measured. Every particle in a field of view was measured. Size-frequency curves (Figs. 17 through 19) were plotted from the results. It was found that the dust particles were far from being uniform in size. The particle size ranged from about 120 μ to below 3 μ. Three μ was the approximate lower limit of particle size that could be measured with the microscope used.

The particle-size-frequency plots show that the separator was more effective on particles above 40 μ than on those below 40 μ. The most important fact that was brought out by the particle-size determinations was that the separator was effective on particles as small as 10 μ. This is evident because of the high frequency of occurrence of particles of this size in the blowdown dust.

The mean weight diameter for the input dust was found to be 49 μ. The mean weight diameter was computed by the formula[7]

(5) Harwell, C. W., "An Initial Study of a Louver-Type Dust Separator," M.S. Thesis, Georgia Institute of Technology, School of Mechanical Engineering, 1950, p. 28.

(6) Dalla Valle, J. M., "Micromeritics," 2nd Edition, Pitman Publishing Corp., New York, N. Y., 1948, pp. 68-70.

(7) Same as above, p. 47.

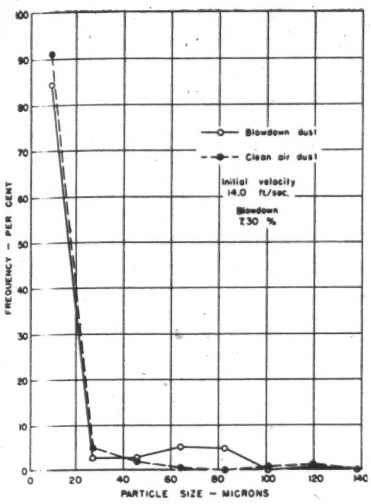

Fig. 18. Particle-Size Distribution of Blowdown and Clean Air at 14.0 ft./sec., Initial Velocity.

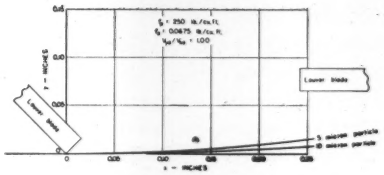

Fig. 20. Theoretical Particle Paths near Louver Opening.

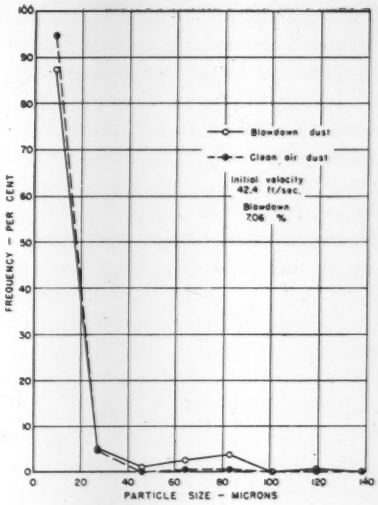

Fig. 19. Particle-Size Distribution of Blowdown and Clean Air at 42.4 ft./sec., Initial Velocity.

$$D_{mw} = \left(\frac{\Sigma n D^3}{\Sigma n}\right)^{1/3}$$

where

n = number of particles in any size group
D = mean diameter of size group
Σ = summation

The mean weight diameter is the diameter of a particle such that if the weight of this particle is divided into the total weight of a sample the result will be the total number of particles in the sample; that is, it is the diameter of the particle of average weight. The mean weight diameter may be in error because the number of large particles that were measured was so small that the measurement of 1 or 2 more large particles would appreciably affect the mean weight diameter.

The mean diameter for the input dust sample was 25 μ.

Idealized Analysis of Particle Paths

Nomenclature:

A = projected area of a dust particle
C_d = coefficient of drag
D = particle diameter
D_{mw} = mean weight diameter
m = mass of a particle
n = number of particles
t = time
V_x = x-velocity of a particle
V_{xa} = x-velocity of air
V_{xr} = x-velocity of a particle relative to air
V_y = y-velocity of a particle
V_{ya} = y-velocity of air
V_{yo} = y-velocity of a particle the instant after an impact
V_{yr} = y-velocity of a particle relative to air
x = distance down louver face
y = distance normal to x
ρ_a = density of air in separator
ρ_p = density of a dust particle
Σ = summation

Particle Paths Near an Opening through Louver

In order to understand better the action of the separator, an idealized analysis of the particle paths has been developed. This analysis is helpful in understanding the results of the tests, and it may prove helpful in predicting the effect of other variables not studied at this time. The analysis is in 2 parts, the first being an analysis of the drag effect on a particle as it passes an opening between the blades, and the second being an analysis of a particle path after an impact with the inclined portion of a louver blade.

It is assumed that the dust particles are smooth spheres. The dust particle that just misses the tip of a blade is analyzed, and it is assumed that the particle passes the tip of the blade with a velocity equal to the velocity of the air stream down the louver face. It is also assumed that the particle is traveling in the direction of the inlet-air stream. As the particle passes the blade tip it passes into the air stream that is flowing between the blades. It is assumed that this air stream is of uniform velocity directed between the blades and is perpendicular to the inlet air stream. The assumptions about the air flow are admittedly approximations.

Let x be the measure of the distance down the louver face in the direction of the inlet-air stream. Let y be the measure of the distance through the louver face normal to x. Let the tip of the blade which the particle just misses be $x = 0$, $y = 0$. Let $t = 0$ be the time at which the particle in question passes through $x = 0$, $y = 0$.

The differential equation governing the x-motion of the particle is

$$m\frac{dV_x}{dt} + C_d A \rho_a \frac{V_x^2}{2} = 0$$

with the initial conditions:

$$V_x = V_{xa} \text{ at } t = 0$$

Because of the turbulence of the main air stream, the coefficient of drag for the particle is taken equal to 0.44, the value for fully developed turbulent motion of the air

about the particle. This is in accordance with DallaValle.[8] Although the average velocity of the particle relative to the air over some short time interval may not be high enough to satisfy the criteria for fully developed turbulent motion of the air about the particle, the turbulent fluctuations of the air stream cause the instantaneous relative velocity between the air and the particle to be high enough for turbulent motion of the air about the particle. Hence, if the air stream through which the particle is passing is itself in turbulent motion, the motion of the air about the particle will be turbulent regardless of the value of the average relative velocity between the air and the particle.

The differential equation governing the y-motion of the particle after $t = 0$ is

$$m \frac{dV_y}{dt} - C_d A \rho_a \frac{V_{yr}^2}{2} = 0$$

with the initial conditions

$$V_y = 0 \text{ at } y = 0$$

On solving the 2 differential equations and eliminating the parameter t, the equation of the particle path[9] is

$$y = \frac{D\rho_p}{0.33\rho_a} \left\{ \frac{V_{ya}}{V_{xa}} \left(e^{\frac{0.33\rho_a x}{D\rho_p}} - 1 \right) - \ln \left[\frac{V_{ya}}{V_{xa}} \left(e^{\frac{0.33\rho_a x}{D\rho_p}} - 1 \right) + 1 \right] \right\}$$

It is important that velocity appears in the expression only as the ratio V_{ya}/V_{xa} which is the ratio of the velocity of the air down the louver face to the velocity of the air between the louver blades. This shows that the particle paths near the openings between the blades are independent of the initial air velocity because, if the initial air velocity is changed, the velocity between the blades will be changed by the same ratio, and the ratio of the velocity down the louver face to the velocity between the blades will remain unchanged.

For a separator operating with uniform velocity down the louver face, the V_{ya}/V_{xa} ratio is determined by the ratio of blade frontal area to blade open area. Since the V_{ya}/V_{xa} ratio is the factor which determines the deflection of a given particle, the expression shows that the particle deflection may be decreased by lowering the ratio of blade frontal area to blade open area.

If, as has been previously discussed, a louver is operating with a decreasing velocity down the louver face, the velocity between the last blades is high and the velocity down the face in front of the last blades is low. Thus the last blades will have a high V_{ya}/V_{xa} ratio and a corresponding large particle deflection.

The particle-path expression shows how the size of a particle affects its path. The paths of a 5-μ and of a 10-μ particle have been plotted in Fig. 20. The plot shows that the deflection of a 10-μ particle is small and that the deflection of larger particles is even less than that for the 10-μ particle. The small deflection of the 10-μ particle apparently explains the effectiveness of the separator on particles as small as 10 μ.

The curves of Fig. 21 have been plotted in order to bring out more clearly how the size of a particle affects its deflection. The curves show the deflection, y, after 0.25 in. travel in the x-direction for different particle sizes. Curves also are plotted to show the effect of different V_{ya}/V_{xa} ratios. The expression for the particle paths indicates that particles of the same density diameter product should have the same particle paths.

Particle-Paths after Impact with Inclined Portion of Louver Blade

A similar analysis can be made of the particle paths after an impact with the inclined portion of the louver blade. As before, the particles are assumed to be spheres. It is assumed that the particle in question travels in a straight line in the direction of the inlet-air stream and impacts the inclined blade surface near the tip. Since the blade is at 45° to the inlet-air stream the assumed spherical particle will rebound with a velocity normal to the inlet-air stream. Let x be the measure of the distance down the louver face in the direction of the inlet-air stream. Let y be the measure of the distance normal to x away from the louver face. Let the point of impact be the point $x = 0$, $y = 0$. Let $t = 0$ be the instant of impact. Let V_{yo} be the velocity of the particle after impact. If it is assumed that the particle rebounds into an air stream of uniform velocity, V_{xa}, the differential equation governing the motion of the particle after $t = 0$ are

$$m \frac{dV_x}{dt} - C_d A \rho_a \frac{V_{xr}^2}{2} = 0$$

$$m \frac{dV_y}{dt} + C_d A \rho_a \frac{V_{yr}^2}{2} = 0$$

with the initial conditions

$$V_x = 0$$
$$V_y = V_{yo} \quad \text{at } t = 0$$

On solving the 2 differential equations and eliminating the parameter t, the equation of the particle path is

$$x = \frac{D\rho_p}{0.33\rho_a} \left\{ \frac{V_{xa}}{V_{yo}} \left(e^{\frac{0.33\rho_a}{D\rho_p} y} - 1 \right) - 1n \left[\frac{V_{xa}}{V_{yo}} \left(e^{\frac{0.33\rho_a}{D\rho_p} y} - 1 \right) + 1 \right] \right\}$$

The details of the solution[9] are the same as for the solution of the paths near a louver opening.

In this expression for the particle paths the ratio V_{xa}/V_{yo} is important. If it is assumed that the particle

(8) Dalla Valle, "Micromeritics," 2nd Edition, Pitman Publishing Corp., New York, N. Y., 1948, pp. 39-40.

(9) See footnote 9, p. 57.

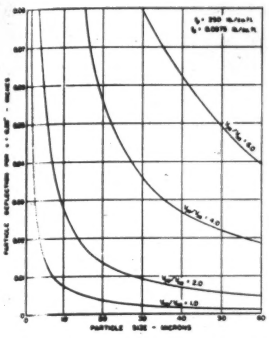

Fig. 21. Theoretical Particle Deflections for $x = 0.25$ in.

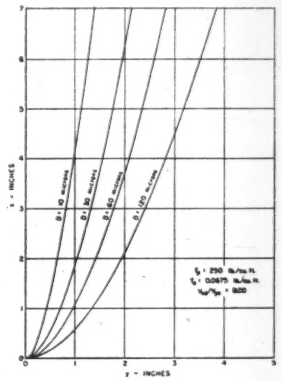

Fig. 22. Theoretical Particle Paths after an Impact.

before impact is traveling with the velocity of the air down the louver face, then the ratio V_{xa}/V_{yo} is the ratio of the speed of the particle before impact to the speed of the particle after impact. It seems reasonable that the ratio of the speed of the particle before impact to the speed of the particle after impact will be about the same regardless of the initial velocity. If this is true, then the initial air velocity will not affect the particle paths after impact. Observations of the particle paths after impact did not reveal a marked change of the paths with changes in the initial air velocity.

The paths for 4 different particle sizes are plotted in Fig. 22. A value of 8 for the V_{xa}/V_{yo} ratio was arrived at for these curves. This value gave particle paths which closely resembled the particle paths observed in the separator.

The V_{xa}/V_{yo} ratio is undoubtedly dependent upon the nature of the particles. Since the V_{xa}/V_{yo} ratio is one of the factors which determines how effectively the particles are moved away from the louver face, it is a factor which must be considered when an attempt is made to predict the effectiveness of the separator on some other dust. If the particles have a low V_{xa}/V_{yo} ratio, the front-wall effect will become important. If the particles have a high V_{xa}/V_{yo} ratio, the particles will remain close to the louver face and have many opportunities to pass through a louver opening.

The limitations of this analysis of the particle paths must be kept in mind; the analysis is definitely only a first approximation.

Conclusions

The most important conclusion that can be drawn from this investigation is that the performance of the separator can be maintained at low blowdown flows if the louver housing is designed so that the velocity of the air stream down the louver face is constant from inlet to blowdown. It was found that the uniform velocity of the air stream down the louver face was necessary to insure a uniform flow through the louver face. A nonuniform flow through the louver face was detrimental to the separator performance because the increased velocity between the last blades of the louver enabled more particles to pass between these blades. The decreased velocity between the first blades of the louver did not decrease the number of particles passing between these blades enough to compensate for the increased number of particles passing between the last blades.

It was found that the straight flat-blade design did not develop the full capabilities of this type of separator. The flat-blade design is such that the particles impact the blade surface in the region where the air is passing between the blades. Thus, after impact with the blade surface the particles have a low momentum and are easily carried between the blades. The new blade design overcomes these difficulties by separating the region of particle impact from the region where the air is passing between the blades.

Performance tests of the redesigned separator showed that the per cent of the dust separated was essentially independent of the initial dust concentration. The tests also showed that the per cent of dust separated was essentially independent of the initial air velocity. This conclusion was supported by the fact that the observed particle paths were not changed to a great extent by changes in the initial air velocity and by the fact that the analysis showed the particle paths to be independent of the initial air velocity.

It was found that at low initial air velocities the performance of the separator could be maintained with a total pressure drop through the separator of less than ½ in. of water.

Particle-size studies on dust samples from the clean air and from the blowdown showed that the separator was effective on dust particles as small as 10 μ. The effectiveness of the separator on particles of this size was supported by the analysis of the particle paths.

The approximate analysis of the particle paths also showed how the ratio of blade frontal area to blade open area, the size of the blade opening, the particle size, the ratio of particle density to air density, and the ratio of the speed of the particle before impact with the blade surface to the speed of the particle after impact might affect the performance of the separator.

The foregoing conclusions should be considered in view of the experimental observation that bottom, top and front-wall effects in the test apparatus contributed to the passage of particles through the louver face. The use of a 3-dimensional full-conical unit will eliminate these problems.

Summary

A preliminary study of the particle paths in a 2-dimensional louver separator was conducted to determine which design features are conducive to good performance. To test the conclusions of the preliminary study, a 30° sector of a conical separator was constructed and its performance studied. The effectiveness of a separator was

evaluated by determining the influence of per cent blowdown, initial air velocity, and initial dust concentration on the per cent of the initial dust separated. The particle-size distributions of the input dust, the separated dust, and the nonseparated dust were compared to bring out the effectiveness of the separator on different particle sizes. The particle paths in the separator were studied and correlated to the separator performance. Throughout the investigation, the particle paths were made visible by reflected light. The air-flow pattern through the separator was found to be the controlling factor in the performance; hence, the shape of the housing on both sides of the louver is of utmost importance. The flow pattern with the same flow through each louver opening was found to be the most desirable. This flow pattern was present when the velocity of the blowdown portion of the inlet-air stream was constant from inlet to blowdown. The effect of the per cent blowdown was correlated to changes in the air-flow pattern, and it was found that the performance of the separator could be maintained at low blowdown flows if the louver housing was designed to provide a desirable flow pattern at the specified blowdown flow. From the particle-path studies, it was concluded that an effective louver-blade shape separates the region of particle impacts with the blade from the region where the air is passing between the blades. The particle-size studies showed that the separator was effective on particles as small as 10 μ and that the separator was more effective on particles above 40 μ. The data from the separator showed that the per cent of the initial dust separated was essentially independent of the initial air velocity and of the initial dust concentration. An approximate analysis of the particle paths was developed which is helpful in explaining the trends in the experimental data.

Acknowledgment

The authors express their gratitude to Research Corporation in making funds available to conduct this study.

(Continued from page 50)

Effect of Fly Ash Characteristics

high draft losses and therefore are more expensive to operate and involve higher capitalization charges than electrostatic collectors; (2) with an inertial collector ahead of the precipitator, removal of the ash from the precipitator plates is more difficult, and also it usually becomes necessary to provide rappers for the corona wires; and (3) inertial collectors are subject to plugging when boilers are fired with oil, due to formation of sticky ash deposits.

In placing combination inertial-electrostatic collectors in proper perspective, it is important to observe that the inertial collector is used as an adjunct to the precipitator, since precipitators can achieve efficiencies of 99% or better unaided, while inertial collectors for fly ash are in general limited to maximum efficiencies of only 75 or 80%. This basic fact may be overlooked in discussions centering on the minutiae of the problem, but becomes apparent when it is realized that, for example, in order to achieve an over-all efficiency of 99% in a combination unit, the precipitator still must perform at 96% efficiency, and this on the finer particles which in general are the more difficult to collect.

Conclusion

In conclusion, collector performance is greatly influenced by the diverse physical and chemical characteristics of fly ash encountered in practice. The ash characteristics are measurable, but for projected boilers (which form the large majority of collector installations) are not in most cases accurately predictable. This complicates collector design and in some cases necessitates extensive changes in collector equipment after construction in order to meet unusually adverse ash characteristics.

In general, conservative design is indicated, since collectors are expected to perform satisfactorily for whatever type of ash may happen to occur. However in some situations economic pressures may predominate and be reflected in inadequate equipment and poor performance. Advances and improvements in collector technology have in part kept pace with the increasing demands on gas-cleaning equipment in the fly ash field, but the diverse and frequently unpredictable properties of the ash have been complicating factors.

The most promising directions for future advances include: (1) development of new collector methods and equipment which will be more independent of ash characteristics; (2) development of better methods for coping with high-resistivity ashes; (3) development of precipitators to operate at higher gas velocities; and (4) methods and principles for predicting and controlling fly-ash characteristics through better fundamental understanding of the factors governing fly-ash formation in furnaces. Research and development work on the broad fly-ash collection problem is bringing these objectives nearer to realization. However, continuing and even closer co-operation between the users and designers of collection equipment will be necessary to achieve mutually satisfactory solutions of the ever-increasing problems in this field.

(Continued from page 20)

Economics of Vapor Recovery

is somewhat better than might be expected, inasmuch as (in general) it would be expected that the economic "cream" had already been skimmed at the time that the rule was passed. It might be mentioned also that all payout times are probably somewhat optimistic, since sometimes excess butane may be diverted to fuel in the summer time.

It is unfortunate that the general public has the impression that the control of emissions by the petroleum industry has been by compulsion only. The status of vapor recovery from storage tanks at the time of the passage of Rule 56 is only one example of prior efforts by the industry. As a matter of fact, the passage of Rule 56 simply accelerated similar programs already under way in many companies. The industry has been and is equally active in reducing emissions of hydrocarbons from other sources to the atmosphere, and the extent of this action goes beyond those required by the rules of the Air Pollution Control District.

Summary

1. Hypothetical cases have been presented, showing that payout times for vapor-loss-reduction systems may vary from 2.6 yr. to infinity, depending upon the size of tanks, the number of tanks, the turnover, and the vapor pressure of the material being handled.
2. A payout time of 10.0 yr. for the actual installations made under Rule 56 has been indicated, and it has been shown that this estimate is reasonable by comparison with the hypothetical cases, particularly when consideration is given to the status of vapor recovery at the time that the rule became effective.

(Continued from page 36)

Adsorption of Binary Hydrocarbon Mixtures

tem. attributed the discrepancy to the fact that Lewis reported data for pressures higher than 1 atmosphere.

Total Gas Adsorbed

The data shown on Fig. 3 reveal that more gas was adsorbed when operating pressure was higher, as could be expected from the published literature. In all cases, the presence of the second gas seemed to decrease the charcoal adsorption capacity for the first gas; and the total amount of gas adsorbed was always smaller than the weight which one would expect for the heavier component alone. This would indicate that formulas given by Markham and Benton[3] are in qualitative agreement with these experimental data.

Fig. 3 presents curves for the system ethylene-propane, prepared by plotting the weight of adsorbed gas/gm. of charcoal vs. time. To compare these values with those of pure hydrocarbons, data for pure butane and propane, at equilibrium conditions, have been included (Ref. curves). Further observation of these curves, and comparison with those of the other systems, indicates also that longer time is required to reach equilibrium when the run is carried on at a lower pressure.

Finally, to compare with Holmes' data, the molecular weight of adsorbed gas for 1 of the runs made by Holmes[1] was calculated and included in Fig. 2. It appears that, despite similar final equilibrium values, Holmes' data

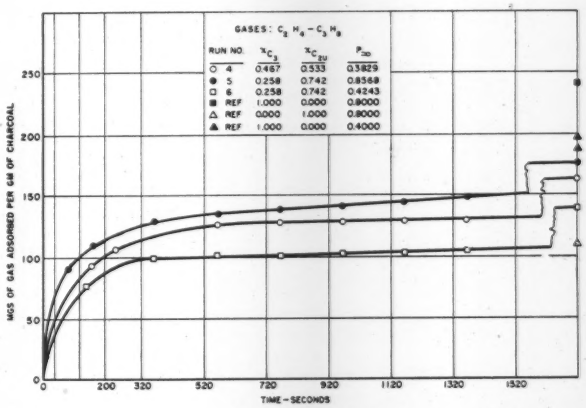

Fig. 3. Rate of Adsorption: Effect of Composition of Adsorbate and Pressure.

indicate less time in reaching the equilibrium state. He attributed the shorter time recorded in his research, in comparison to the time reported by Mulvany,[4] to the larger amount of charcoal used by the latter. His conclusion seems to be correct, since the present writers used a larger amount of charcoal in their research than did Holmes, and a longer time was required to reach equilibrium.

(1) See footnote 1, page 36.

(3) Markham, E. C., and Benton, A. F., *J. Am. Chem. Soc., 53,* 497 (1931).

(4) Mulvany, P. K., "Studies Concerning the Rates of Adsorption and Desorption of Some Low Molecular Weight Hydrocarbons and Their Binary Mixtures," Ph.D. Thesis, University of Washington (1950).

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